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FROM THE

MOUNT WILSON SOLAR OBSERVATORY

VOLUME III

NOS. 53–69

WITH TWENTY-FOUR PLATES

MARCH, 1911—DECEMBER, 1912

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THE EFFECT OF PRESSURE UPON ELECTRIC FURNACE SPECTRA

By ARTHUR S. KING

The effect of high pressure around the light-source in displacing the spectrum lines given by the arc and spark has been studied to such an extent that the general phenomena are well known. Measurements of the shift of lines for arc spectra through a considerable range of pressures and for a number of elements have been published by Humphreys[1] and by Duffield.[2] The effect of pressure upon electric furnace spectra is a new field, involving some phenomena peculiar to the apparatus.

The electric resistance furnace in the Pasadena laboratory was described by the writer[3] at the time of its construction and has since been used extensively in the study of the effect of varying temperatures upon spectra. The furnace chamber was built for high pressures, having been tested hydraulically to 5000 lbs. per square inch. A series of experiments has been made recently to observe the effect of pressure on the furnace spectrum, and although the work has been entirely in the nature of a preliminary survey, the results show clearly what is to be expected from the apparatus in this line of research.

EXPERIMENTAL METHOD

1. *The furnace.*—The furnace was used for this investigation with only slight changes. The tubes of Acheson graphite used at first were 30.5 cm long, 12.5 mm inside diameter and 18.5 mm outside diameter. In later experiments resistance tubes of the same length and inside diameter but of 19.5 mm outside diameter

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[1] *Astrophysical Journal*, **26**, 18, 1907.

[2] *Philosophical Transactions of the Royal Society of London*, A, **208**, 111, 1908; **209**, 205, 1908; **211**, 33, 1911.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

were used. A length of 38 mm at each end of the tube was clamped in the vertical graphite blocks which connected the ends of the tube with the water-cooled copper pipes carrying the current. The heated portion of the tube between the contact blocks was then 22.9 cm long. This portion was protected first by a graphite tube of 32 mm inside diameter to provide a clear space immediately about the heated tube, then by carborundum powder heaped around the outer tube to serve as a heat jacket.

The pressure-chamber was modified only by the use of conical glass windows 21.5 mm thick in the water-cooled window-holders, and by simple connections for the gas tank and gauges to one of the holes in the head of the furnace chamber, while a valve with connection for rubber tube was screwed into the other hole. Two gauges were used on the apparatus, one hydraulic, the other a low-reading gas pressure gauge. After allowing for the difference of one atmosphere in their scales, the gauges always agreed in their readings within 5 pounds.

When ready for use, a vacuum pump was connected to the valve last mentioned, and the furnace with connecting tubes was pumped out to less than 1 cm of mercury. A potential of 15 volts A.C. gave an initial current of about 900 amperes with the thinner tubes described above, and 1000 to 1100 amperes with the thicker ones. The current would quickly fall 50 amperes or more as the tube heated, then very slowly if there was no opportunity for oxidation. A photograph taken under these conditions gave the first part of the comparison for a pressure exposure. On the completion of this preliminary exposure, the outlet valve was closed, the vacuum pump disconnected, and the chamber filled with gas to the desired pressure. The furnace is almost perfectly air tight, so that the pressure of the gas would rise rapidly from contact with the heated parts within. To prevent this, the outlet valve was either frequently opened or set so as to give a constant leak sufficient to counteract the increase of pressure within. At the conclusion of the pressure exposure, the valve was opened and the gas reduced to atmospheric pressure, after which the vacuum pump was again connected and the furnace pumped out for the second portion of the comparison photograph.

2. *The optical system.*—The photographs were made with the 30-ft. (9.1 m) vertical Littrow spectrograph. The grating used was ruled by Michelson, and has a ruled surface 19 cm wide, with 500 lines per mm. The second-order spectrum was used, giving a scale of about 0.95 Å per mm. The light from the furnace was focused on the slit by means of a simple lens 10 cm in diameter and of 60 cm focal length. The position of this lens was so adjusted that the grating was centrally illuminated by a beam of light about twice the diameter of the 20 cm objective of the spectrograph. The method of making comparison exposures was to leave all parts of the optical system absolutely untouched between exposures, except for a moving of the sliding occulting plate above the slit, which is supported independently of the latter. The first comparison exposure in vacuum was made with the plate so adjusted as to give two narrow strips of spectrum. The pressure exposure was then placed between these. For the second exposure in vacuum the plate was moved back to its first position with its two openings adjusted to give longer strips of spectrum. The comparison spectrum was thus made up of the superposition of exposures taken before and after the pressure photograph, with the lines due to the second exposure usually extending a little beyond the superposed portion. The slightest instrumental disturbance was then shown by the imperfect coincidence of the comparison lines.

The furnace with the optical system as described gives a minimum risk of instrumental disturbance, since there need not be the least movement of anything which can affect the direction of the beam of light. The furnace supplies its own comparison spectrum, and this being taken in vacuum, the pressure-effect is that due to the total pressure, not to the excess of the furnace pressure above one atmosphere.

THE GAS USED, AND SPECIAL PHENOMENA

For these preliminary observations, commercial carbon dioxide in cylinders was employed, being the most easily obtained of any gas which would serve. Compressed air is out of the question for furnace work, as the large supply of oxygen would cause the furnace tube to be quickly consumed. Considerable oxidation has resulted from the use of carbon dioxide, as the gas dissociates from contact with the hot tube and the surrounding jacket which is raised to red heat for a considerable distance from the tube itself. The free oxygen given off causes the tube to wear thin near its ends, where the gas comes most freely in contact with the graphite. More serious than the wearing of the tube is the formation of a white smoke, probably an oxide, which becomes rather thick at high pressure and weakens the light by collecting in the end of the furnace tube as well as in the steel chamber, where it deposits on the cool metal parts as a white powder. This probably results from the contact of carbon dioxide with the heated carborundum, which is the most efficient jacketing material thus far found for the regular use of the furnace. The formation of white vapor increases with the pressure and sets a limit to the effective use of carbon dioxide. Some other material for heat insulation, combined perhaps with the use of compressed hydrogen, may give an improvement in this direction.

Two refraction effects are noticeable. One is a trembling of the image of the interior of the tube as projected on the slit of the spectrograph. This increases with the pressure, but is not disturbing at moderate pressures. The other is an interesting bending of the beam of light within the furnace owing to the fact that the gas in the lower half of the chamber is cooler than that above, there being a length of about 20 cm of compressed gas between the end of the tube and the window with the arrangement thus far used. The image on the slit was moved about 3 mm when the chamber was filled to 9 atmospheres and in the direction to be expected according to this explanation. The effect decreases after the furnace has been heated some time and the gas has become of more uniform temperature throughout. As the image on the slit is over 1 cm in diameter, there is no difficulty in adjusting at the beginning so as to allow for this movement. The effect cannot influence the pressure results, as it amounts only to taking the light from a slightly different part of the cross-section of the tube. There is no appreciable change either in intensity or wave-length of the lines given by different portions of the cross-section, as the stigmatic action of the Littrow spectrograph readily shows.

The temperature of the furnace was regulated by the impressed voltage to give a large number of lines without strong continuous spectrum, the effect of a very high temperature being to widen the lines and the reversals and eventually to give all lines in absorption when the continuous spectrum became strong enough.

Temperature measurements were made during the production of both the pressure and the comparison spectra, a Wanner pyrometer being sighted on the interior of the furnace tube through the window opposite to that directed at the spectrograph.

Pyrometer readings are made to best advantage when a graphite plug is placed midway in the tube, which gives a close approach to black body conditions; but this is impracticable when observations of the spectrum are being made. The pyrometer recorded temperatures ranging from 2100° to 2300° C. under the regular conditions of operation. There was always a close agreement between the temperature readings with and without pressure for the same current through the tube, so long as the light from the furnace was not weakened by smoke during the operation under pressure.

RESULTS

1. *Nature of pressure-effect for the furnace.*—Pressure in the furnace as high as 9 atmospheres gives a clear displacement of all lines toward the red, the magnitude of the displacement varying greatly for different lines. The general effect is a widening combined with displacement, the degree of widening also being very different for different lines and having no apparent relation to the amount of displacement. It has been noted in previous publications that the furnace, as regularly used in vacuum, does not give strong widening except for a few lines, generally those appearing in low-temperature flames, for which the amount of vapor present seems to govern the width. With pressure, however, the furnace not only gives this class of lines enormously widened, usually beyond the possibility of close measurement, but the widening extends to a second class of lines, requiring higher temperature than the first mentioned though appearing at the lower furnace temperatures (usually under 2000° C.). Such lines are always strong with the furnace in vacuum,

though not greatly widened. They appear in the high-temperature flames and in the outer vapors of the arc. The effect of pressure upon these lines is to give very strong widening, usually combined with reversal, since the lines are also given by the cooler vapor near the ends of the furnace tube. The reversals are quite or very nearly symmetrical, indicating that the displacing effect of pressure upon the cooler vapor is the same as upon the hotter. These widened lines in the spectra thus far examined never show the largest shifts. As a rule the displacement is of medium amount, but sometimes is very small.

Lines which appear at the higher furnace temperatures show various degrees of widening, though never so large as the lines just discussed, and a very great variety of displacements. The largest shifts occur for such lines. As a rule they appear unreversed and moderately widened as compared with their condition with the furnace in vacuum. Sometimes the effect of pressure is almost or entirely to blot out a line. In most cases I think this is due to a rather strong widening of a weak line, since generally a very hazy trace of the line can be seen in the pressure photograph. No clear case has been observed of a line being rendered visible by pressure when the photograph without pressure was taken at about the same temperature and normally exposed. The effect of pressure appears to be confined to a widening and displacing of such lines as are brought out by the temperature employed.

The quality of the furnace lines for measurement is in general good, perhaps better than is usually given by the arc under pressure. The reversals are well defined and generally narrow. If the exposure is not greatly prolonged, the conditions of the furnace can be controlled more closely than probably is possible for any other source.

2. *Comparison with pressure results for the arc.*—The portion of the iron spectrum from λ 4060 to λ 4460 photographed with the furnace under pressure has been studied by Duffield[1] with the pressure arc, and a comparison with his results has led to two interesting conclusions. The measurements of furnace pressure plates showed that the displacements for the majority of the lines

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[1] *Philosophical Transactions of the Royal Society of London*, A, **208**, 111, 1908.

fall into three groups for which the ratio of the shifts is 1:2:4. The same relation, and in general for the same lines, was found by Duffield for the arc displacements. The good quality of the furnace lines for measurement gives this grouping very distinctly. Without any decided exception thus far observed, the relative displacements for furnace lines follow closely those for the arc. This is for two sources which have a considerable difference in temperature and which are shown by other effects to have the luminous vapor in a very different condition as regards response to the displacing influence of pressure.

The second important result in the comparison with the arc shows that *for the same pressure the furnace displacements are much larger than those of the arc.* This was established by a series of plates taken at 8 and 9 atmospheres total pressure, the magnitude of the shifts being found to run about 100 per cent larger than those given by Duffield for the same lines at 11 atmospheres and to agree closely with the arc displacements for 21 atmospheres. The superposition of the comparison spectra taken before and after the pressure exposure showed freedom from instrumental disturbance, and the relation was further shown decisively by the grouping of displacements in the 1:2:4 ratio mentioned in the preceding paragraph. An instrumental displacement of all lines would be added to the true shifts, and with the values observed for 9 atmospheres the 1:2:4 ratio would not hold even approximately.

The later measurements by Humphreys[1] of arc displacements for iron do not go lower than 42 atmospheres, but the shifts recorded are found to be in general rather less than twice those given by the furnace at 9 atmospheres, so that there is a fair agreement.

Table I gives the furnace displacements in thousandths of an Ångström unit measured on the best plate (F 140) taken at 9 atmospheres total pressure, the comparison spectrum being with the furnace in vacuum. The measurements of this plate were fully checked by four other good plates taken under the same pressure conditions. In the third and fourth columns are measurements for the same lines by Duffield at 21, and by Humphreys at 42 atmospheres. Two sets of measurements are given by Duffield, and

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[1] *Op. cit.*

TABLE I

Pressure Displacements

Iron

λ	Furnace 9 Atm.	Arc, 21 Atm. (Duffield)	Arc, 42 Atm. (Humphreys)	Remarks
4063.759....	0.064	0.062	0.107	Reversed
4071.908....	0.060	0.067	0.092	Reversed
4100.901....	0.028	.....	.....	
4132.235....	0.102?	0.064	0.105	Reversed. Measurement disturbed by close blend with *V* line
4134.840....	n.m.	0.032	.....	Much weakened by pressure. Small displacement
4143.572....	n.m.	0.060	.....	Faint. Medium displacement
4144.038....	0.065	0.068	0.116	Reversed
4147.836....	0.058	.....	.....	
4152.343....	0.041	.....	.....	
4154.667....	n.m.	0.054	.....	Faint. Medium displacement
4156.970....	n.m.	0.054	.....	Faint. Medium displacement
4172.296....	0.099	.....	.....	Much widened
4172.923....	0.044	.....	0.140	
4174.095....	0.030	.....	.....	
4175.082....	0.034	.....	.....	
4177.698....	0.037	.....	.....	
4181.919....	0.085	0.043	.....	Faint
4185.058....	n.m.	.....	0.040	Faint. Medium displacement
4187.204....	0.111	0.128	.....	
4187.943....	0.114	0.094	.....	
4191.595....	0.119	0.271	.....	
4198.494....	0.125	0.127	.....	
4199.267....	0.026	0.043	0.073	
4200.148....	0.039	.....	.....	
4202.198....	0.062	0.044	0.071	Reversed
4206.862....	0.033	.....	.....	
4210.494....	0.113	0.142	.....	
4216.351....	0.033	.....	.....	Reversed
4222.382....	0.106	0.265	.....	
4232.887....	0.027	.....	.....	
4233.772....	0.101	0.107	0.240	
4236.112....	0.119	0.125	0.274	
4250.287....	0.126	0.083	.....	
4250.945....	0.060	0.057	0.089	Reversed
4258.477....	0.035	.....	.....	
4260.640....	0.124	0.124	0.246	
4271.325....	n.m.	0.075	.....	Weakened. Blend with wide reversal of 4271.934
4271.934....	0.063	0.064	0.083	Reversed
4282.565....	0.039	0.032	0.043	
4291.630....	0.030	.....	.....	
4294.301....	0.063	0.050	0.084	Reversed
4299.410....	0.126	0.126	.....	
4306.078....	0.075	.....	.....	
4308.081....	0.055	0.063	0.090	Reversed
4315.262....	0.042	0.041	0.036	
4325.939....	0.064	0.062	0.097	Reversed
4337.216....	0.062	0.069	0.090	
4347.403....	0.035	.....	.....	

TABLE I—*Continued*

λ	Furnace 9 Atm.	Arc, 21 Atm. (Duffield)	Arc, 42 Atm. (Humphreys)	Remarks
4352.908....	0.049	0.048	0.052	
4376.107....	0.032	0.032	0.039	Reversed
4383.720....	0.068	0.070	0.125	Reversed
4389.413....	0.028	.....	.....	
4404.927....	0.071	0.064	0.110	Reversed
4415.293....	0.067	0.052	0.087	Reversed
4427.482....	0.037	0.028	0.055	Reversed
4435.321....	0.032	.....	.....	
4442.510....	0.097	0.101	0.190	
4443.365....	n.m.	0.047	0.060	Faint. Medium Displacement
4447.892....	0.107	0.121	0.180	
4459.301....	0.096	0.116	0.160	
4461.818....	0.049	0.045	0.060	Reversed
5143.111....	0.057	.....	.....	
5151.020....	0.067	.....	.....	
5152.087....	0.061	.....	.....	
5166.454....	0.033	.....	.....	
5167.678....	0.051	.....	.....	Reversed
5169.069....	0.051	.....	.....	
5171.778....	0.052	.....	0.075	
5195.113....	0.056	.....	0.080	
5216.437....	0.037	.....	.....	
5225.695....	0.021	.....	.....	
5227.362....	0.052	.....	.....	
5233.122....	0.160	.....	.....	Weak and diffuse
5247.229....	0.055	.....	.....	
5250.385....	0.024	.....	.....	
5250.817....	0.113	.....	.....	Faint
5255.121....	0.029	.....	.....	
5266.738....	0.169	.....	.....	Faint
5269.723....	0.056	.....	0.083	Reversed
5270.558....	0.064	.....	.....	
5283.802....	0.083	.....	.....	Faint
5324.373....	n.m.	.....	.....	Much weakened. Large displacement
5328.236....	0.062	.....	0.100	Reversed
5328.696....	n.m.	.....	.....	Blend with reversal of 5328.236
5333.089....	0.051	.....	.....	
5341.213....	0.057	.....	.....	
5371.734....	0.068	.....	0.095	Reversed
5397.344....	0.060	.....	0.080	Reversed
5405.989....	0.051	.....	0.100	Reversed
5429.911....	0.059	.....	0.085	Reversed
5434.740....	0.057	.....	0.120	Reversed
5447.130....	0.068	.....	0.095	Reversed
5455.834....	0.065	.....	0.105	Reversed
5497.735....	0.063	.....	0.110	
5501.683....	0.060	.....	0.095	
5507.000....	0.062	.....	0.120	

Chromium

λ	Furnace, 9 Atm.	Humphreys, 42 Atm.
4254.505	0.037	0.056
4274.958	0.056	0.076
4289.885	0.048	0.087

Vanadium

λ	Furnace, 9 Atm.	λ	Furnace, 9 Atm.
4099.941	0.046	4384.873	0.067
4105.318	0.062	4390.149	0.061
4109.95	0.042	4395.413	0.065
4111.940	0.067	4400.738	0.044
4115.330	0.056	4406.810	0.067
4128.251	0.042	4407.810	0.064
4134.589	0.025	4408.364	0.059
4330.189	0.037	4408.683	0.063
4332.988	0.046	4459.922	0.061
4341.167	0.048	4460.389	0.064
4379.396	0.066		

where these are very different for a certain line, the value was used which most nearly accords with a linear relation between pressure and displacement.

The measurements for the region from λ 5143 to λ 5507 were made from a very good plate (F 141) taken under conditions as nearly identical as possible with those for the previous plate in the blue region. This is the only plate thus far taken in the green with the furnace under pressure, as it was highly satisfactory. The experiments have been concentrated on the blue region because of the great variety of displacements present there and the opportunity to compare with the arc results. There is every reason to believe that the displacements measured for the two parts of the spectrum correspond to the same furnace conditions. Values for the arc displacements of the green lines as measured by Humphreys for 42 atmospheres are given in a separate column.

The three strong blue lines of chromium were measured and the displacements are entered with the arc values of Humphreys, the ratio of furnace and arc shifts being about the same as for iron.

The iron filings used in the furnace proved to contain enough vanadium to give the stronger lines of this substance, which are accordingly listed, as measurements for this element are very scanty.

The remarks in the last column refer to the appearance of the furnace lines under pressure. The letters "n.m." denote that the line was not measurable in the pressure spectrum, but enough could be seen to give an estimate of the order of magnitude of the displacement, which is entered in the "remarks" column. The wavelengths are on the Rowland scale.

The plates were measured with a small Gaertner comparator by Miss Griffin and myself. The quality of most of the lines was such that separate sets of measurements agreed to within 0.01 Å.

Nearly all of the furnace lines for iron between λ 4060 and λ 4460 fall into three groups, for which the mean displacements show a close approach to the 1:2:4 ratio, as shown by Table II.

TABLE II

GROUPING OF FURNACE DISPLACEMENTS

Group	No. Lines	Mean Displacement
I	20	0.034
II	15	0.064
III	15	0.112
Intermediate	2	0.049

A comparison, in Table III, of the mean displacements of those lines common to my tables and those of Duffield shows the close correspondence between the grouping for the furnace and the arc.

TABLE III

MEAN DISPLACEMENTS FOR FURNACE AND ARC

Group	No. Lines	Furnace	Arc
I	5	0.035	0.035
II	13	0.064	0.061
III	14	0.113	0.138
Intermediate	2	0.049	0.047

3. *Anomalous displacements under special conditions.*—The photographs thus far discussed were taken with the furnace in vacuum for the comparison spectrum and at a pressure which gave displacements of considerable size without introducing dis-

turbing conditions. It appeared possible to reproduce at will the shifts given under these conditions, only one plate, of poor quality, showing any appreciable discordance with the set thus taken.

A variation of conditions, however, has shown that the displacements for the furnace do not depend entirely upon the pressure, but may be influenced by the state of the vapor in the furnace tube in a way which at present is not clear.

The use of a pressure above 9 atmospheres or the presence of carbon dioxide at atmospheric pressure during the preliminary comparison exposure gives in either case a large increase in the white smoke previously referred to. Pressure photographs have then occasionally given displacements larger or smaller than those normally obtained. The most striking instance of this kind was a plate taken with carbon dioxide at atmospheric pressure during the comparison exposure, then with the pressure raised to 9 atmospheres above atmospheric pressure, instead of to 8 atmospheres as was usual for the best plates when the comparison was taken in vacuum. On this plate the shifts were almost twice as large as those given normally by the same difference in pressure with the comparison in vacuum, therefore about four times as large as for the arc at equal pressure. The plate was apparently free from instrumental disturbance and the ratio of 1:2:4 for different lines held as before. Several attempts were made to obtain these large displacements again, but the conditions could not be kept uniform for different runs as they can with the furnace in vacuum, and the smoke usually gave underexposure. One fairly good plate taken in this way gave shifts very close to those regularly obtained for 9 atmospheres with the comparison in vacuum. Another anomalous plate was taken for 11 atmospheres total pressure, the comparison being in vacuum. For this plate the shifts agreed closely with those of the arc for 11 atmospheres, being about half as large as the furnace usually gave for 9 atmospheres. An attempt to repeat this plate gave displacements of the magnitude to be expected for 11 atmospheres, being a little greater than normally obtained for 9 with the furnace.

4. *Influence of temperature and vapor-density.*—The effect of difference of temperature was tested by a plate for a total pressure

of 9 atmospheres with a temperature, as read by the Wanner pyrometer, about 300° higher than that regularly employed. The difference was probably considerably greater than this, as the increased amount of smoke in the furnace due to the high temperature tended to reduce the reading. In spite of weakening of the light from this cause, the exposure for a strong photograph was only one-third of that required for the lower temperature. The high temperature photograph gave displacements consistently 10 to 25 per cent smaller than those for the temperature regularly used.

A photograph taken under the usual conditions but with a very little iron in the tube gave displacements of about the usual magnitude, though the lines were faint and poor for measurement.

These results will be taken up later in the discussion.

5. *Evidence on the linear relation between displacement and pressure.*—The proportionality between pressure and displacement has not been fairly tested with the furnace, as a much greater range of pressures is required than has been used as yet. However, a comparison is given in Table IV for the displacements of a number of good lines measured for 6, 8, 9, and 11 atmospheres, the comparison spectra being always taken in vacuum. A regular increase is evident, indicating that a linear relation probably holds if the conditions of the furnace are properly controlled.

TABLE IV

CHANGE OF DISPLACEMENT WITH PRESSURE FOR SELECTED LINES OF IRON

λ	DISPLACEMENTS			
	6 Atm.	8 Atm.	9 Atm.	11 Atm.
4250.945.....	0.048	0.051	0.060	.....
4271.934.....	.038	.061	.063	0.082
4308.081.....	.040	.044	.055	.076
4325.939.....	.033	.057	.064	.070
4376.107.....	.018	.031	.032	.037
4383.720.....	.034	.051	.068	.071
4404.927.....	.042	.052	.071	.075
4415.293.....	.023	.058	.067	.064
4427.482.....	.023	.030	.037	.037

6. *Data concerning the relation between pressure-displacement and Zeeman separation.*—A comparison of the pressure-effect with the

magnetic separation for lines of the iron spectrum was given in a former paper,[1] using the pressure measurements of Humphreys and Duffield. The furnace material enables us to compare the average displacements and separations for two regions of the spectrum about 1000 Ångström units apart. The average displacement for the total number of lines in the two regions cannot be compared with fairness at present, as most of the weaker lines in the green were too faint for the measurement of their displacements and the largest pressure effects usually occur among lines of this class. With the available material it seemed best to select lines showing a similar behavior in laboratory sources, as these probably arise from vibrating particles having at least some points of similarity. Such lines are those which appear at low temperatures of the furnace and reverse easily. Fifteen lines of this character are included in the region from λ 4050 to λ 4450 given in Table I, and 9 lines between λ 5050 and λ 5450, excluding λ 5434.740, which is not comparable, being unaffected by the magnetic field. Assuming that the pressure plates were taken under similar conditions, we see that the displacements of these lines show no tendency to change with the wave-length, the mean shift being 0.058 for the blue and 0.060 for the green lines. (The very close agreement is of course largely accidental.) The magnetic separations for these lines, however, show a decided increase with the wave-length, although the separations of the lines in each region are of the same order of magnitude. For a field-strength of 16,000 gausses, the mean separation of the 15 blue lines given as "reversed" in Table I is 0.330, while that for the 9 green lines is 0.520, an increase of 60 per cent for a difference of wave-length of about 1000 units. This affords further evidence against a close connection between the phenomena of pressure and of the magnetic field.

7. *The adaptability of the furnace to pressure investigations.*—While it is too early to state definitely the limitations of the furnace as a pressure source, a few points may be noted as to the relative usefulness of the furnace and arc in this line of work. In the total number of lines produced under pressure, there is little to choose

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 46; *Astrophysical Journal*, **31**, 433, 1910.

between them. The tables for iron given by Duffield and in the present paper contain almost exactly the same number of lines for the same range of wave-length, though the lists are not identical owing to the difference in relative intensity of lines given by the furnace and arc. Nineteen lines measured by Duffield could not be measured on the furnace plates, while values for 18 furnace lines are given which do not appear in the arc tables. In the green region, measurements are given for almost double the number of lines measured by Humphreys in the arc, though probably the high pressure used by him increased the difficulty in obtaining the weaker lines.

As to quality, a line clearly and narrowly reversed given by any source usually admits of close measurement. I believe experience will prove that unreversed lines can be measured to better advantage on furnace plates, as there seems to be less tendency toward strong and unsymmetrical widening than is usually given by the arc.

The arc will have an advantage over the furnace in the production of the enhanced lines of some elements, such as titanium, in which most of the lines characteristic of the spark are given of moderate intensity by the arc.

For very high pressures the arc may be more efficient than the furnace, though this is by no means certain, since these preliminary experiments have suggested a large variety of ways in which present difficulties may be overcome. The use of a different compressed gas, different jacketing material, and probably shorter tubes should permit the use of much higher pressures. The relative displacements of lines have been given clearly by the pressures thus far employed.

The chief usefulness of the furnace for pressure work will probably occur when it is desirable to take advantage of the special conditions of radiation afforded by it. The present work has shown that its results may give large differences from those normally obtained with the arc. When an extended investigation has shown what conditions are responsible for these differences, the close control of the state of the radiating vapor which is possible with the furnace will probably open lines of work which cannot be carried out to advantage with any other source.

In astrophysical problems the temperatures involved are high, being approached best by the arc and spark; but in other respects the state of the luminous vapor resembles more nearly that of the furnace, so that certain phases of the pressure phenomena can be studied to best advantage by means of this source.

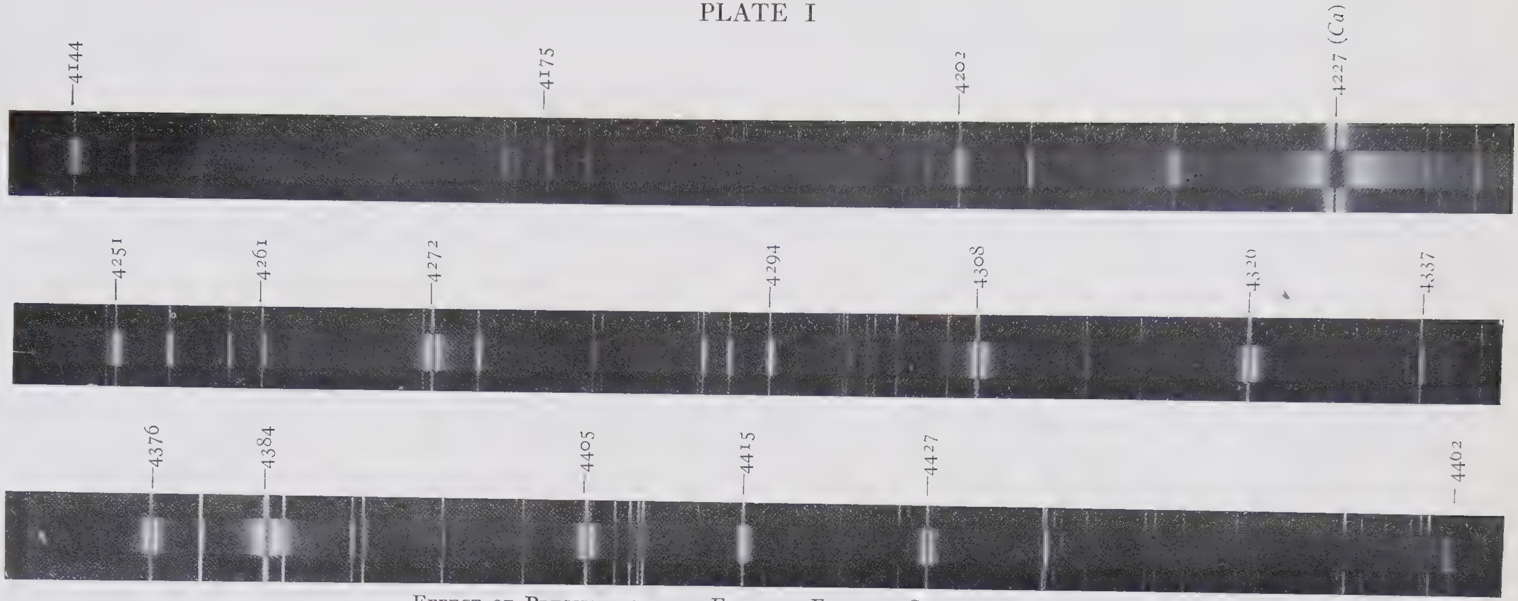
8. *Explanation of the plates.*—Plates I and II present enlargements of the more interesting regions of the iron spectrum covered by the furnace plates. Certain groups of lines are favorable for the examination of the differences in relative magnitude of displacements. In Plate I, the 1:2:4 relation is represented by λ 4258.477, λ 4250.945 or λ 4271.934, and λ 4260.640 respectively. The group of reversed lines near λ 4383.720 shows this line with λλ 4404.927 and 4415.293 displaced approximately twice as much as λλ 4376.107 and 4427.482. An example of the very wide reversal of flame lines is given by λ 4227 of calcium, arising from impurities. The same degree of reversal was obtained for the three blue lines of chromium when a large amount of this metal was used in the furnace.

Plate II shows a portion of the iron spectrum in the green. The spectrum given by the arc between iron poles is also reproduced for comparison. It is seen that the furnace under pressure gives in this region only lines which are strong and sharp in the arc. The other strong lines, with edges not so sharp, are given by the core of the arc, and appear in the furnace spectrum very faintly at the highest temperatures. The comparison spectrum for the pressure photograph shows a combination of effects owing to the fact that the second comparison exposure, taken with longer slit, ended by the tube burning through, giving during a few seconds a spectrum similar to that for the core of the arc. The result is that the regular furnace lines appear with fainter extensions, while those lines which are not usually given by the furnace show faintly and of uniform intensity throughout their length.

DISCUSSION

It has been the purpose of this paper to record the pressure-effects for the furnace as given by a definite set of experimental conditions, which as yet have been varied only to a limited degree.

PLATE I

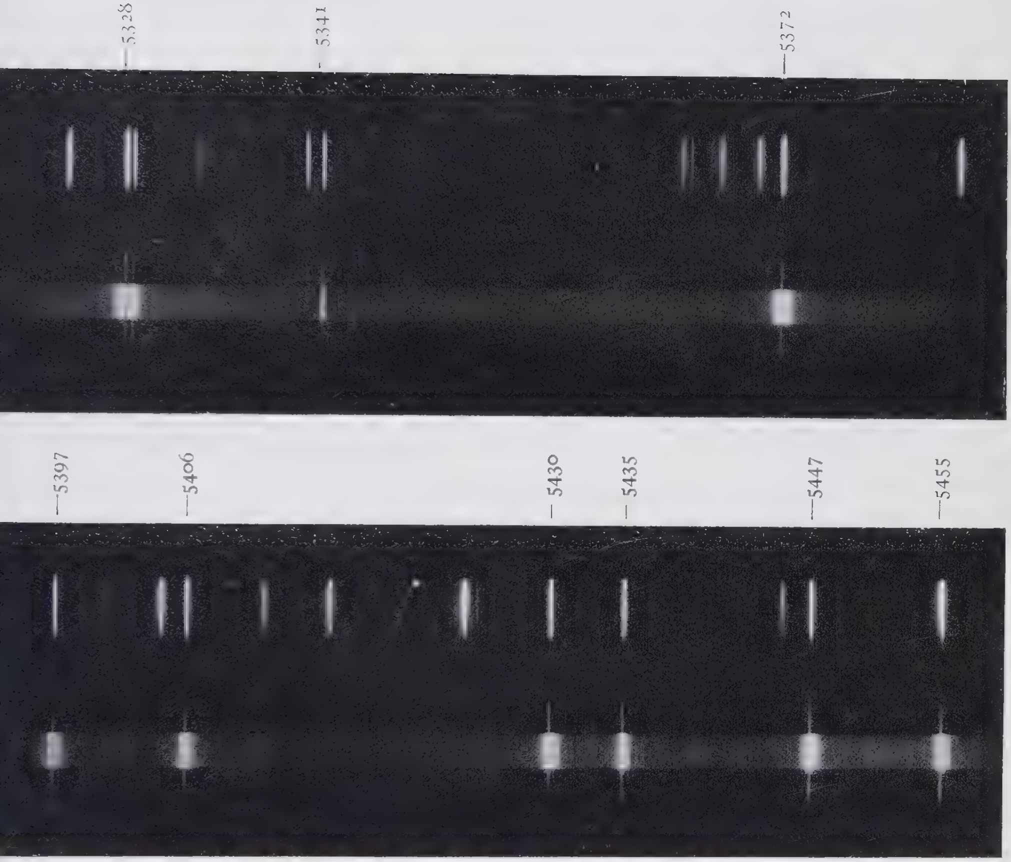


Effect of Pressure on the Electric Furnace Spectrum of Iron

Inner portion of each spectrum given by furnace at 9 atmospheres. Comparison spectrum given by furnace in vacuum

Scale: 1 mm = 0.5 Å

PLATE II



ectrum of iron arc *b*, Effect of pressure on the electric furnace spectrum of iron

Inner portion of spectrum *b* given by furnace at 9 atmospheres

Comparison spectrum given by furnace in vacuum

Scale: 1 mm = 0.5 Å

At this time it would be merely speculative to discuss the results further than to bring out a few leading points in the question as to why the furnace gives displacements consistently larger than those of the arc. The occasional departures from regularity in the furnace effects are to be regarded as a strengthening or weakening of a general displacing influence.

It may be noted that these results have been in a way predicted by observations on the arc under pressure. Workers with the arc have obtained many discordant results for pressures under 20 atmospheres, so that for this range it has been difficult to show a linear relation between shift and pressure. Duffield obtained a plate at 25 atmospheres which gave shifts twice as large as those which accorded with the linear relation. This is a difference of the same magnitude that the furnace at 9 atmospheres gives as compared with the arc at the same pressure. This and other departures from the linear relation observed by Duffield on certain plates were not to be explained by errors of measurement, and are considered by him as probably connected with the tendency to reverse, the reversals of lines being broader and stronger on the plates giving abnormal shifts.

The production of large displacements may arise from causes of two kinds, either or both of which may be active in the furnace. The luminous metallic vapor may be in such a condition as to weaken the resistance offered by the vibrating particle to a change in its period; or the condition of the compressed gas may enable it to exert a stronger displacing influence.

To consider first a possible weakening of the forces controlling the period, we find that the differences observed between the effects of the furnace and the arc indicate that a decrease in the internal energy of radiation, regulated in the case of the furnace by the temperature, may permit a large disturbance of the period by pressure; in other words, that lower temperature may favor large displacements. The result of the test as to the effect of increased furnace temperature showed that the difference produced was in this direction; and as there is probably an interval of at least 1200° between the lower furnace temperature and that of the arc, this might explain in large measure the differences obtained were it not that other lines of evidence indicate that temperature difference in itself cannot fully account for the results. In the first place, those furnace plates which gave differences larger or smaller than regularly obtained were made with the furnace at about the usual temperature. Other evidence is that the reversals for lines with the furnace under pressure are symmetrical, which should not be the case if the cooler vapor near the ends of the tube gives a line of different wave-length from the vapor in the middle. A difference in the amount of iron vapor present in the furnace tube also appeared to be without decided effect.

Evidence from arc investigations may be considered in this connection. The arc under pressure rarely burns steadily, the spectrum of different regions being taken in turn under ordinary conditions. Different investigators have used a variety of arrangements of the arc, including carbon and metallic terminals and the rotating type, and if either temperature or vapor-density exerts a controlling influence, it is doubtful if results for the arc under pressure would show even as much consistency as they do.

The furnace results give little ground to choose between the theories proposed by Humphreys,[1] Richardson,[2] and Larmor[3] to account for the pressure-effect, but since that of Larmor involves the dielectric constant of the luminous vapor, a possible influence upon this quantity may be considered. An increase in the dielectric constant should diminish the elasticity of the ether about each particle of matter, with a resulting tendency toward increase of vibration period. It would seem probable that the difference between the heated vapor in the furnace and the discharge conditions of the arc might give a change in the inductive capacity, but there is little evidence as to its direction or amount. However, Baedeker[4] measured the change of dielectric constant with temperature through various ranges, sometimes as high as 150° C., of several vapors, among them sulphur dioxide, ammonia, ethyl chloride, methylene chloride, and chloroform, and found in all cases a decrease in the dielectric constant with increase in temperature. If this relation is general for gases and holds at very high temperatures, the temperature difference between furnace and arc would change the dielectric constant in the right direction to give larger shifts for the furnace.

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[1] *Astrophysical Journal*, **23**, 233, 1906.

[2] *Philosophical Magazine* (6), **14**, 557, 1907.

[3] *Astrophysical Journal*, **26**, 120, 1907.

[4] *Zeitschrift für physikalische Chemie*, **36**, 305, 1901.

We may also consider whether the effect can be ascribed to the large dielectric constant of carbon dioxide as compared to compressed air. The dielectric constant of air at 20 atmospheres was measured by Occhialini[1] as 1.0101, that for carbon dioxide at 20 atmospheres by Linde[2] as 1.025. This difference in itself should give larger displacements for the furnace in carbon dioxide than for the arc in air, although, as has been remarked by Humphreys, a change directly proportional to the dielectric constant would be within the errors of measurement. Tests have been made of the displacements given by the spark in different atmospheres by Anderson[3] and by Hale and Kent.[4] The former found some evidence of an increased displacement in carbon dioxide as compared with hydrogen. The question was discussed at some length by Humphreys,[5] but a systematic investigation of the effect of different gases under pressure for the arc and spark has not yet been made. It is hoped to make such a comparison at an early date with the furnace. The irregular displacements occasionally obtained when white oxide was present in the furnace can perhaps be most easily explained through a change of the dielectric constant.

One feature in which the furnace conditions are different from those of the arc is that the effect of the compressed gas should be more steady and possibly stronger in the furnace. Here we have the carbon dioxide heated to about the same temperature as the radiating metallic vapor, and with considerable uniformity throughout several inches of the tube, with little circulation. With the arc, the heating of the gas is very much localized, with opportunity for constant movement of the gaseous particles in and out of the heated region. The fact that in the arc the metallic particles carry the greater part of the electric current makes it a question how nearly the thermal condition of the gas approaches that of the metallic vapor.

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[1] *Physikalische Zeitschrift*, **6**, 669, 1905.

[2] *Annalen der Physik und Chemie*, **56**, 546, 1895.

[3] *Astrophysical Journal*, **24**, 221, 1906.

[4] *Publications of the Yerkes Observatory*, **3**, Part II, 1907.

[5] *Astrophysical Journal*, **26**, 18, 1907.

SUMMARY

The results obtained may be summarized as follows:

1. The furnace under pressure gives a spectrum containing practically all lines brought out by the same temperature with the furnace in vacuum.

2. The general effect of pressure is a widening of lines and displacement toward greater wave-length, the widening for low-temperature lines being very strong and usually accompanied by reversal.

3. The number of lines which are measurable is approximately the same as for the arc under pressure, with some differences due to the different relative intensity of lines in the two sources.

4. The displacements of nearly all iron lines from λ 4050 to λ 4450 fall into three groups, the ratio of the displacements being 1:2:4, which ratio was also found for these groups of lines in the arc.

5. So far as observed, the *relative* displacements of the furnace lines appear to follow closely those of the arc.

6. The *absolute* displacements of furnace lines at a pressure of 9 atmospheres are about twice those given by the arc at the same pressure and compare closely in magnitude with the arc displacements for 20 atmospheres.

7. Some furnace photographs have shown shifts larger or smaller than those usually given by the same pressure. These were apparently due to differences which evidently prevailed in the condition of the luminous vapor.

8. For iron lines of the same general character, produced at low furnace temperatures and easily reversed, the displacement shows no tendency to increase with the wave-length, the pressure-effect being in this respect very different from the effect of a magnetic field for the same lines.

I am indebted to Miss Griffin for much assistance in the measurement of the spectrograms.

Mount Wilson Solar Observatory
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MOTION AND CONDITION OF CALCIUM VAPOR OVER SUN-SPOTS AND OTHER SPECIAL REGIONS

By CHARLES E. ST. JOHN

In a former paper, "The General Circulation of the Mean and High-Level Calcium Vapor in the Solar Atmosphere,"[1] the investigation was confined to those portions of the solar disk that were free from spots and flocculi. The points at which measurements were made were 1, 12, 25, 35, 50, and 70 mm from the limb and at the center, on an image 172 mm in diameter. The investigation was continued through 12 rotations of the sun, during which period the position angle of the solar axis described nearly a complete cycle; the points selected for measurement lay along a horizontal diameter of the image produced by the Snow coelostat, and as the plates were taken at irregular intervals each point corresponded to a random distribution of positions on the solar surface but at definite distances from the center of the disk. The combined results of the measurements showed a descending motion for the absorbing vapor of 1.14 km per second, and an ascending motion for the emitting vapor of 1.97 km per second over the surface of the sun. This result, depending on some 500 positions on the solar surface, represents a mean that is practically free from the effects of causes that are occasional and diverse in their action and may be assumed to show the condition of the calcium vapor over regions of the surface not subject to great or exceptional disturbances, such as spots, flocculi, and prominences in projection.

In the present paper are presented the results of an investigation in which the measurements of the wave-lengths of the absorption line K_3 and the emission line K_2 of calcium have been extended over the umbrae and penumbrae of spots, over the accompanying flocculi and circumfloccular regions, and over some other points where the calcium vapor showed exceptional phenomena. Measurements are given also for the intensity of the emission line in terms of the continuous spectrum and for the relative intensities of K_1, K_2, K_3, and for different points of the same line. The series of plates extends over nearly two years. The spectrographs employed are of the auto-collimating type and are described as Nos. 2 and 3 in *Contribution* No. 44.[1] In the 18-foot (5.5 m) instrument (No. 2) a 20-cm Michelson grating having 590 lines to the centimeter, and a 10-cm Rowland grating having 568 lines to the centimeter were used, the scale in each case being approximately 1 mm = 1.0 Å. This instrument can be used as a section-spectrograph, and is an application of the principle of the *spectro-enregistreur des vitesses* suggested by M. Deslandres.[2] The arrangement permits one easily and rapidly to take exposures of successive points or successive exposures of the same point. The majority of plates were taken with this spectrograph, using a second slit 12 mm wide in order to include the solar standards, and 45 mm long, the maximum length of the second slit. Often successive exposures were taken over a spot, but more frequently the first slit was moved by steps of 2 mm each over the region under investigation. The other plates were taken with the 30-foot spectrograph (No. 3) used in connection with the 60-foot tower telescope in which the above-described Rowland grating was used, giving a scale of approximately 1 mm = 0.60 Å. These plates are designated by the letter "*c*."

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 48; *Astrophysical Journal*, **32**, 36, 1910.

The measurements of the spectra were made upon a Gaertner comparator reading directly to 0.001 mm. The plates were measured red right and red left, and at least four settings were made for each position. The two iron lines λ 3930 and λ 3935 were employed as standards. The solar wave-lengths of these lines were determined at the center of the sun in terms of the International Standards as described in *Contribution* No. 48, p. 42.[3] The wave-lengths of these lines at the center of the sun were found to be λ 3930.306 and λ 3935.823, the arc values being λ 3930.301

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[1] *Astrophysical Journal*, **31**, 143, 1910.

[2] *Comptes Rendus*, **114**, 277, 1892.

[3] *Astrophysical Journal*, **32**, 36, 1910.

and λ 3935.818 respectively. Their wave-lengths over the surface of the sun, away from the limb, have been assumed to remain constant except in the immediate neighborhood of sun-spots where the radial motions discovered by Evershed may affect them when the slit is not placed perpendicular to the radius drawn through the spot. To eliminate any such effect it was the practice to make settings on portions of the standard lines outside the penumbral regions which are the seat of the radial motions in the reversing layer. To fix the points of the line at which measurements were to be made, and to avoid the effect that might be produced by having other portions of the line in the field of view, the photographic plate was often covered by an adjustable slide in which there was a slit 1 mm wide and sufficiently long to include the standard lines. The platform of the comparator carried a millimeter scale at each end by means of which the plate could be moved in a direction perpendicular to the screw in order to bring any desired point of the line into the field of view.

Distortions of the H and K lines of calcium are not uncommon during periods of activity and violent changes in and around sun-spots, when eruptions often take place in the immediate vicinity. Displacements of the lines occur at such times, which indicate very high velocities in the line of sight, amounting to one hundred kilometers or more per second. The measurements that form the basis of the present article were made upon plates that did not show such extreme and unusual conditions, but were representative, rather, of the more common and steady states. The purpose has been to determine what is the usual rather than the unusual, to find what are the prevailing movements of the calcium vapor in and around sun-spots, if such movements do exist in any stable form. There is undoubtedly much that is billowy, tumultuous, and apparently irregular in the movements in the upper regions of the solar atmosphere, but it is a question whether underneath the adventitious and casual there may not exist some systematic effects that point to generally acting causes. The present investigation was undertaken mainly to obtain quantitative data bearing upon this question.

TABLE I

The K Line of Calcium over the Umbrae of Central Spots

Plate	Date	Spot	On C.M.	Wave-Length of K Line	Eccentric Distance	Character	Remarks
					mm		
126..........	1908 Dec. 7	6577	1908 Dec. 8.3	3933.680 (4)	37.5	Bright, single	2d apparition. Large, regular. Returned as 6592, 6609, 6627, 6647, and 6661
138..........	Dec. 9	6577	Dec. 8.3	.679 (2)	35.0	Bright, single	Large, regular
				3933.680			
215..........	1909 Jan. 18	6602	1909 Jan. 19.9	.660	26.0	Bright, single	2d apparition. Large, regular. Returned as 6618
219..........	Jan. 19	6602	Jan. 19.9	.658 .655 .652 .650 .655	6.3	Bright, single	On 2 successive days this spot showed from 6 consistent measurements an upward motion over the umbra
				3933.655			
228..........	Jan. 20	6602	Jan. 19.9	.691 .690 .681 .688	14.6	Bright, single	On this, the following day, the motion was strongly downward
				3933.688			
228..........	Jan. 20	6604	Jan. 22.3	.686 (2)	41.8	Bright, single	1st apparition. Large. Regular. Returned as 6621
230..........	Jan. 23	6604	Jan. 22.3	.682 (2)	33.0	Bright, single	Large, regular
				3933.684			

237..........	1909 Jan. 28	6606	1909 Jan. 28.9	3933.675 (3)	31.0	Bright, single	Only appearance. Large, irregular cluster. Active region
247..........	Jan. 29	6606	Jan. 28.9	.676 (4)	29.0	Bright, single	Irregular cluster
				3933.676			
247..........	Jan. 29	6608	Jan. 30.3	.678 (2)	37.4	Bright, single	2d apparition. Large, irregular spot about to break up
257..........	Jan. 30	6608	Jan. 30.3	.682 (3) .665 (5)	28.0	Bright, single	Line strongly curved over umbra showing a change in motion over different parts
263..........	Jan. 30	6608	Jan. 30.3	.683 (5) .667 (1)	28.0	Bright, single	The table gives the means for the 2 parts of the line
				3833.675			
258..........	Jan. 30	6609	Feb. 1.1	.677 (4)	44.5	Bright, single	Large spot. 4th apparition. Return of 6592, a return of 6577
263..........	Jan. 30	6609	Feb. 1.1	.682 (2)	44.5	Bright, single	Large, regular
				3933.679			
290..........	Feb. 24	6625	Feb. 26.5	.693 (4)	40.0	Bright, single	1st apparition. Large, regular. Returned as 6645
296..........	Feb. 25	6625	Feb. 26.5	.685 (6)	25.2	Bright, with dark center	λ for weak absorption line 3933.684 (4)
304..........	Feb. 26	6625	Feb. 26.5	.687 (3)	27.0	Bright, with dark center	λ for weak absorption line 3933.685 (3)
309..........	Feb. 27	6625	Feb. 26.5	.694 (2)	42.4	Bright, single	Regular
				3933.689			
304..........	Feb. 26	6627	Feb. 28.5	.679 (3)	54.5	Bright, with dark center	5th apparition. Return of 6609. λ for absorption line 3933.673 (3)
309..........	Feb. 27	6627	Feb. 28.5	.678 (4)	44.0	Bright, single	Spot shows indications of breaking up
				3933.678			

TABLE I—*Continued*

Plate	Date	Spot	On C.M.	Wave-Length of K Line	Eccentric Distance	Character	Remarks
	1909		1909		mm		
439	April 24	6660	April 24.6	3933.684 (2)	C'ntr'l	Bright, single	Large, regular spot. One apparition
563	July 23	6695	July 24.4	.684 (2)	11.0	Bright, single	Large, regular spot. Leader of stream
567	July 24	6695	July 24.4	.679 (4)	10.0	Bright, single	Regular
				3933.681			
617	Oct. 20	6746	Oct. 20.7	.687 (2)	15.0	Bright, single	Large spot. 2d apparition. Returned as 6765
621	Oct. 30	6753	Oct. 31.4	.679 (2)	18.2	Bright, single	3d apparition. Large, regular spot. Line weak
624	Oct. 31	6753	Oct. 31.4	.678 (4)	C'ntr'l	Bright, single	Line weak
				3933.678			
649*a*	Nov. 6	6756	Nov. 6.4	.682 (2)	19.0	Bright, single	Large, regular. 2d apparition. Leader of train. Returned as 6778
649*b*	Nov. 6	6756	Nov. 6.4	.686 (3)	19.0	Bright, single	Regular
				3933.685			
651	Nov. 15	6765	Nov. 17.0	.674 (3)	27.5	Bright, single	3d apparition. Return of 6746
652	Nov. 16	6765	Nov. 17.0	.671 (1)	17.4	Bright, single	Regular
653	Nov. 16	6765	Nov. 17.0	.685 (3)	17.4	Bright, single	Regular
660	Nov. 17	6765	Nov. 17.0	.697 (1)	18.3	Bright, single	Regular
				3933.682			
669	Nov. 27	6771	Nov. 26.7	.687 (3)	36.0	Bright, single	1st apparition. Large, regular. Returned as 6786
674	Nov. 27	6772	Nov. 26.7	.665 (4)	21.0	Broad, bright	4th apparition. One of changing group
679	Nov. 28	6772	Nov. 26.7	.667 (2)	22.0	Broad, bright	Strong, bright line
				3933.666			

680..........	1909 Nov. 28	6774	1909 Nov. 27.4	3933.670 (2)	27.0	Bright, single	One of developing group
714..........	Dec. 23	6786	Dec. 24.0	.696 (6)	29.5	Bright, single	Large, regular. Return of 6771. Line weak
714..........	Dec. 24	6787	Dec. 24.9	.690 (2)	29.0	Bright, single	Large, regular. Return of 6771
716..........	Dec. 24	6787	Dec. 24.9	.693 (4)	29.0	Bright, single	Large, regular
				3933.692			
714..........	Dec. 23	6788	Dec. 25.1	.688 (2)	44.0	Bright, single	Large, regular. Return of 6774
717..........	Dec. 24	6788	Dec. 25.1	.681 (4)	27.0	Bright, single	Large, regular. K line weak
				3933.683			
76*c*..........	1910 May 18	6847	1910 May 18.6	.688 (2)	20.0	Bright, single	Regular
76*c*..........	May 18	6849	May 19.7	.684 (2)	19.0	Bright, single	Large, regular. Leader of stream. Shows inflow of calcium vapor on plates taken near limb
79*c*..........	May 19	6849	May 19.7	.691 (3)	C'ntr'l	Bright, single	Large, regular
				3933.688			
195*c*..........	Aug. 9	6874	Aug. 9.5	.684 (3)	C'ntr'l	Bright, single	Large, regular. Shows inflow. Terrestrial magnetic disturbances. Returned as 6880
256*c*..........	Sept. 27	6886	Sept. 26.9	.687 (2)	C'ntr'l	Bright, single	Large, regular. 2d apparition
296*c*..........	Oct. 21	6897	Oct. 21.3	.683 (2)	25.0	Bright, single	Shows inflow on plates taken near limb. At first absorption line showed even with fine seeing. Later only bright line

VERTICAL MOTION OF CALCIUM VAPOR OVER THE UMBRAE OF SPOTS

The usual appearance of the K line of calcium over spot umbrae is that of a relatively narrow but actually broad bright line, its width being approximately 0.3 Å. See Plate III (*a*). Compared with the line over the surrounding faculae it is broader than K_3 and narrower than K_2. Occasionally there is superposed upon it a narrow absorption line. This is often due doubtless to photospheric light that reaches the slit when the seeing is poor. The question whether it is ever a real spot phenomenon will be discussed later in the paper. The measurements were confined to the plates obtained when the spots were near the central meridian. The average diameter of the solar image was 170 mm. On an image of this diameter the vertical component of the motion of the rising or falling vapor at a point 35 mm from the center of the disk is about 10 per cent less than at the center. Few of the spots upon which measurements were made were so far from the center. Not all the plates were taken for this investigation, and the most available have been selected from those already on hand. Table I gives the results of the measurements. The Greenwich spot numbers are in the third column; the wave-length of the bright K line of calcium is given in the fifth column in International Units; the figures in parentheses following the wave-lengths show the number of separate measurements upon which the result depends; in the main these refer to separate exposures on the same plate. The distances of the spots in millimeters from the center of the image are given in the sixth column. In the last column under "remarks," the history and description of the spot are outlined, and the wave-lengths of the absorption line K_3 are included. The spots are arranged serially in the order of their appearance. The wave-length of the K line of calcium in the arc in International Units, to which the wave-lengths in the spots may be referred for the purpose of determining the motion of the calcium vapor, is λ 3933.667, as determined in *Contributions* No. 44, p. 10.[1]

Of the twenty-five spots studied, one, 6577, was observed at three apparitions; and four, 6746, 6771, 6772, and 6774, were observed at two apparitions. Twenty-two spots showed at all times a downward movement of the vapor producing the bright K line of calcium. The velocity of descent varied for individual spots from 0.68 km per second in the case of 6606 to 2.2 km per second in the case of 6789, the general mean being 1.30 km per second. Spot 6602 gave some interesting results. On the first two of the three days on which observations were obtained the calcium vapor was rising with a velocity of 0.9 km per second. On the following day it was descending with a velocity of 1.6 km per second. This sudden change in the direction of the movement of the vapor was so surprising that the plates were remeasured. The results were similar, as indicated by the individual measurements given in full in the table. Spot No. 6608 was a large spot approaching dissolution. The bright calcium line over the umbra was strongly curved. The portion displaced to the violet was the brightest and the measurement indicated a possible upward velocity of the vapor of 0.15 km per second. The measurement of the portion of the line displaced to the red indicated a downward velocity of 1.22 km per second. The result given in the table for this spot is the mean, and indicates on the whole a considerably greater velocity downward than upward. The interesting fact, however, is that two parts of the umbra show these different conditions. The measurements in the case of spot 6772 point to a practically stationary state of the vapor producing the bright line, namely, an upward motion of less than 0.1 km per second. On its return as 6787 the emitting vapor was descending with a velocity of 1.9 km per second. From the large percentage (88 per cent) of the spots showing only downward movement of the emitting vapor and from the varying results for the other spots, one can conclude that in the umbrae of spots the calcium vapor is in general descending, but that under certain conditions upward motions do occur.

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[1] *Astrophysical Journal*, **31**, 152, 1910.

VERTICAL MOTION OF CALCIUM VAPOR OVER THE PENUMBRAE OF SPOTS

The usual appearance of the K line of calcium in the penumbra of a spot is very similar to that over the surrounding flocculus, consisting of the two bright components of K_2 and the central dark line K_3, except that the width of the K_2 line decreases rapidly as it nears the umbra and the absorption line grows less distinct and finally disappears over the umbra. These two portions of the line lie, of course, upon the broad shading of K_1, which is not considered in the wave-length measurements, as it is not possible to fix its position with sufficient accuracy. Both K_2 and K_3 have been measured; the center of the bright line was obtained by adding to the wave-length of the violet component the difference of wave-length between the absorption line and the red component.[1] Upon plates taken as these were, near the center of the solar image, the line usually runs straight over flocculus, penumbra, and umbra. No correction for distance from the center has been made to the wave-lengths in Table I, but in Table II, containing the results of the measurements over the penumbrae of the spots, the data for the umbrae of the individual spots are given with such corrections, which in no case exceed 0.002 Å.

TABLE II

THE K_2 AND K_3 LINES OF CALCIUM OVER THE PENUMBRAE OF CENTRAL SPOTS

NUMBER	NORTH		UMBRA	SOUTH		REMARKS
	K_2	K_3		K_2	K_3	
6577	3933.665(5)	3933.681(5)	3933.681	3933.680(5)	3933.692(5)	2d apparition. Returned as 6592
6602	.633(2)	.661(2)	.655	.643(2)	.676(2)	For 2 days
	.658(2)	.685(2)	.688	.662(2)	.690(2)	On the following day
6604	.668(1)	.685(1)	.686	.691(1)	.686(1)	1st apparition
6606	.677(2)	.671(2)	.677	.679(1)	.668(1)	Only appearance
6608	.661(2)	.671(2)	.676	.667(2)	.678(2)	2d apparition, about to break up
6609	.657(5)	.670(5)	.681	.679(3)	.686(3)	Return of 6592
6625	.670(2)	.684(2)	.690	.666(2)	.684(2)	1st apparition. Returned as 6645
6627	.681(2)	.692(2)	.680	.659(2)	.680(2)	Return of 6609
6660	.684(4)	.685(4)	.684	.692(3)	.684(4)	Only appearance
6695	.657(1)	.674(1)	.681	.672(1)	.687(1)	Leader of stream
6746	.684(1)	.684(1)	.687	.670(1)	.686(1)	2d apparition
6753	.651(4)	.674(4)	.678	.659(4)	.674(4)	3d apparition
6756	.674(5)	.689(5)	.685	.667(5)	.680(5)	2d apparition
6765	.653(4)	.678(4)	.681	.661(4)	.675(4)	Return of 6746
6771	.658(3)	.688(4)	.688	.632(3)	.659(3)	1st apparition
6772	.653(2)	.678(2)	.666	.654(3)	.675(3)	1st apparition
6774	.661(1)	.672(1)	.670	.648(1)	.684(1)	Developing spot
6786	.680(2)	.689(2)	.697	.670(2)	.680(2)	Return of 6771
6787	.667(4)	.694(4)	.693	.659(4)	.679(4)	Return of 6771
6788	.662(4)	.673(4)	.684	.668(4)	.678(4)	Return of 6774
6847	.665(2)	.694(2)	.688	.672(2)	.683(2)	1st apparition
6849	.685(1)	.689(1)	.688	.672(1)	.681(1)	Shows inflow
6874	.681(1)	.681(1)	.684	.666(1)	.661(1)	Shows inflow and vortex
6886	.655(1)	.653(1)	.687	.666(1)	.687(1)	
6897	.674(1)	.678(1)	.683	.684(1)	.696(1)	Shows inflow
	3933.665(63)	3933.682(63)	3933.682	3933.665(57)	3933.679(57)	

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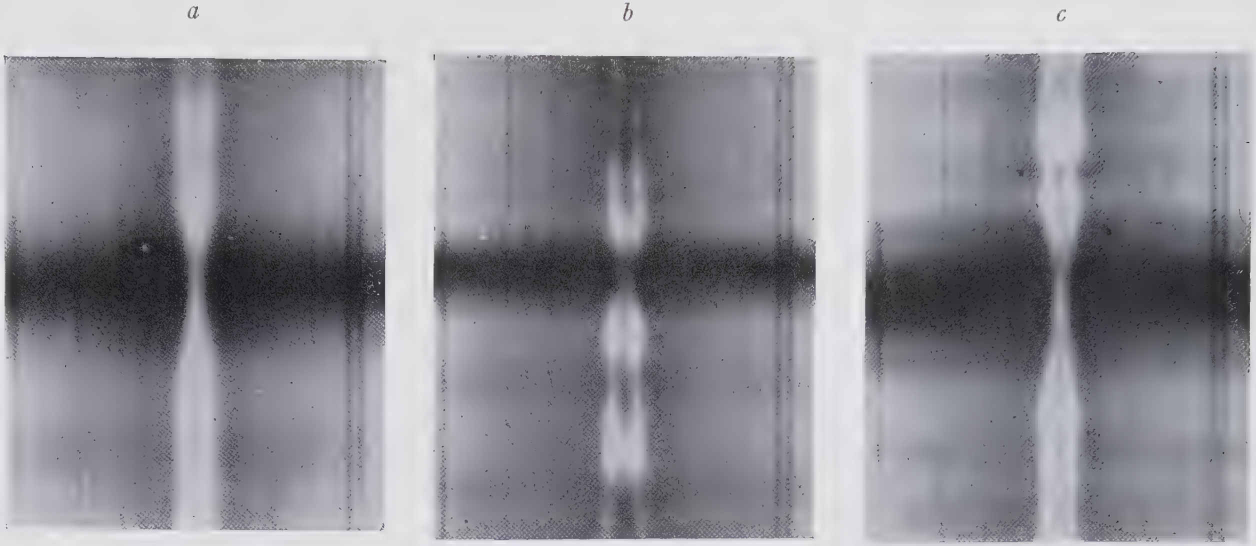
[1] Adams, *Contributions from the Mount Wilson Solar Observatory*, No. 6, 3, 1905; *Astrophysical Journal*, **23**, 47, 1906.

PLATE III



The K Line of Calcium over Sun-Spot No. 6874

Enlargement: 6 times from original negatives with the 30-foot spectrograph and tower telescope

a, Normal reversal over umbra. Spot central. 1910, August 9.

b, Displacements due to inflow of penumbral vapor. Slit parallel to solar radius through spot, 17 mm from east limb. 1910, August 5.

c, Displacements due to rotation of penumbral vapor. Slit perpendicular to solar radius through spot, 23 mm from west limb. 1910, August 12.

The headings "north" and "south" are not to be taken too literally, as they refer only to opposite sides of the spots in a very general north-and-south direction. The separation into these two groups was made in order that the results of the two independent sets of measurements might serve as checks upon each other. The mean of the two surprisingly concordant results for the emitting vapor is 3933.665. The measurements are difficult to execute, but considerable reliance may be placed on the final mean, depending as it does upon 120 measurements. The wave-length in the arc being 3933.667 Å, it appears that in the penumbrae of spots the calcium vapor producing the emission line is on the average neither ascending nor descending, as the mean would imply an upward velocity of only 150 m per second. The variation in the wave-length of the K_2 line in the penumbrae of different spots is greater than the errors of measurement in some cases, and should not be left out of consideration in the discussion of the individual spots. The high-level absorbing vapor is descending with a velocity of approximately 1 km per second, if its wave-length be referred to 3933.667. The measurements carried out on the absorption line K_3 reported in *Contribution* No. 48[1] point to a slightly shorter wave-length at the limb of the sun, where on the whole the effect of line-of-sight motion was probably eliminated; and, moreover, at the elevation at which the absorption line is produced, the pressure is probably less than one atmosphere, which is the value to which the arc wave-length is referred.

VERTICAL MOTION OF CALCIUM VAPOR OVER FLOCCULI

In Table III are assembled the results of the measurements of the wave-lengths of the K_2 and K_3 lines of calcium over the surrounding flocculi and outside the penumbral region of the spots. Points were taken on flocculi north, south, east, and west, and at different distances from the spots in order that the mean might fairly represent the average condition over the flocculi.

The division of the table into two parts was, as in the preceding one, for the purpose of using the two sets of measurements as checks upon each other. The K_2 line is very difficult to measure, because its components over the flocculi are very broad and each component is bounded differently on its two edges—on one edge by the K_1 shading and on the other by the K_3 line, and these boundaries are of different intensities. Moreover, the intensity of the K_2 component falls off more gradually toward the K_1 shading than toward the K_3 line. The plates have been measured red right and red left, with from four to ten settings on each component in each position. It was found of advantage to use the adjustable slide over the plate to fix the portion of the line under measurement, and to eliminate as far as possible effects that might arise from the rapidly varying width of the bright component. In general these components appear to the eye to be of nearly equal widths over the flocculi.

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[1] *Astrophysical Journal*, **32**, 36, 1910.

TABLE III

The K_2 and K_3 Lines of Calcium over Central Flocculi

Number	North and East		South and West	
	K_2	K_3	K_2	K_3
6577.........	3933.677(2)	3933.679(2)	3933.680(2)	3933.696(2)
6602.........	.643(2)	.667(2)	.657(2)	.671(2)
6604.........	.648(3)	.682(2)	.673(2)	.676(1)
6606.........	.677(2)	.670(2)	.678(1)	.674(1)
6608.........	.656(2)	.665(2)	.678(2)	.682(2)
6609.........	.650(3)	.666(3)	.670(6)	.677(5)
6625.........	.675(3)	.685(3)	.663(3)	.683(3)
6627.........	.659(3)	.673(3)	.667(3)	.680(3)
6660.........	.683(2)	.689(2)	.689(2)	.688(2)
6695.........	.680(7)	.681(5)	.676(7)	.690(6)
6746.........	.670(4)	.685(4)	.661(4)	.677(4)
6753.........	.658(10)	.673(8)	.663(3)	.680(2)
6756.........	.657(4)	.688(4)	.664(6)	.680(6)
6765.........	.654(2)	.685(2)	.666(6)	.678(6)
6771.........	.660(2)	.678(2)	.644(2)	.659(2)
6772.........	.657(3)	.682(3)	.653(7)	.665(7)
6774.........	.633(2)	.660(2)	.646(2)	.679(2)
6786.........	.666(3)	.682(3)	.658(3)	.679(3)
6787.........	.651(5)	.684(5)	.651(5)	.678(5)
6788.........	.659(6)	.675(6)	.671(8)	.689(8)
6847.........	.684(2)	.695(2)	.672(2)	.684(2)
6849.........	.681(3)	.691(3)	.667(3)	.666(3)
6874.........	.677(2)	.676(2)	.673(2)	.667(2)
6880.........	.666(3)	.676(3)	.675(2)	.680(2)
6886.........	.663(3)	.679(3)	.666(2)	.683(2)
6897.........	.672(2)	.685(2)	.656(3)	.686(3)
	3933.663(85)	3933.679(80)	3933.665(90)	3933.679(86)

The marked dissymmetry that is evident over the central portion of the disk outside of the flocculi shows but slightly, partly because the components are so broad, but mainly because it does not exist to the same degree. The mean wave-length for the two closely agreeing sets depending upon 175 measurements is 3933.664 Å against 3933.667 Å in the arc and 3933.641 Å at the center of the disk.[1] This indicates a small ascending movement of 0.23 km per second for the emitting vapor, against an upward velocity of 1.97 km per second for this vapor over the general solar surface. There are some indications in the measurements at different distances from the spot that the upward movement increases with increasing distance, but the number of measurements is not sufficient to fix this point. This result for the bright calcium over the flocculi is not in agreement with the general assumption that over the flocculi this vapor is rising rapidly from the interior of the sun or from a hotter lower stratum. The present investigation has been confined to the usual conditions in the flocculi and has not dealt with the exceptional eruptive phenomena. No measurements are known to the writer supporting the assumption of rapid upward motion, which seems to rest upon what appeared to be a very natural explanation of spectroheliographic data.

VERTICAL MOTION OF CALCIUM OVER CIRCUMFACULAR REGIONS

In the previous paper, "The General Circulation of Calcium Vapor," the measurements of the K_3 line were limited to regions free from spots and faculae. In the present investigation such measurements have been extended to the facular and circumfacular regions in order to detect any local circulation that might have its seat there, and to determine whether the facular and circumfacular regions are in any way complementary to each other. The measurements are given in Table IV and refer to the faculae surrounding the spots investigated, which were always near the center of the disk.

The mean of all the measurements is 3933.678, but omitting spots 6771, 6772, 6774, which appear to form a group by themselves, the mean is 3933.680. The mean of 166 measurements of the wave-lengths of K_3 over faculae is 3933.679. In the paper "The General Circulation of the Calcium Vapor" already referred to, the wave-length of the K_3 line at the center of the sun was found to be 3933.680, and in the arc 3933.667. The agreement between the means of the three solar determinations is so close that it seems evident that the conditions obtaining in the case of the upper calcium layer of the solar atmosphere are the same over the general surface, the faculae, and the region immediately surrounding the faculae; and that a local system of circulation between the facular and circumfacular regions is not the usual condition in the high-level vapor. Twenty-six circumfacular regions were investigated, twenty-three of which show a descending motion of the absorbing vapor at every point at which measurements were made. These points have been taken on all sides and at varying distances from the edges of the brilliant flocculi. In nine cases out of ten, therefore, the measurements indicate a descent of the high-level calcium vapor in the regions surrounding the faculae. In a tenth of the cases, namely in the circumfacular regions of spots 6771, 6772, and 6774, the mean of the measurements is 3933.665 Å. Compared with wave-length 3933.667 in the arc this would indicate a possible upward motion of 150 m per second; but the outstanding differ-

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 48, 21, 1910; *Astrophysical Journal*, **32**, 56, 1910.

TABLE IV

THE K_3 LINE OVER CIRCUMFACULAR REGIONS

Spot Number	Wave-Length	Spot Number	Wave-Length
6577	3933.681(1)	6765	3933.672(6)
6602	.676(5)	6771	.668(6)
6604	.684(4)	6772	.666(5)
6606	.683(4)	6774	.661(5)
6608	.687(4)	6786	.682(8)
6609	.686(9)	6787	.677(3)
6625	.684(6)	6788	.677(5)
6627	.678(7)	6847	.675(3)
6660	.685(3)	6849	.680(3)
6695	.673(10)	6874	.687(6)
6746	.681(4)	6880	.679(4)
6753	.676(5)	6886	.672(3)
6756	.681(5)	6897	.677(1)

Mean.......................... 3933.678(134) ence of 0.002 Å is too small to predicate motion upon, and moreover the low pressure at this high level might account for the slight difference, as the shift per atmosphere is only 0.002 Å. Reference was made above to the possibility that these three spots form a special group. They were on the disk at the same time; two of them, 6771 and 6772, crossed the central meridian at the same hour; spot 6772 crossed 0.7 day later. It is of interest in this connection to compare the entire set of measurements at their following apparitions as 6786, 6787, and 6788, and with the mean of the whole series of spots. These data are assembled in Table V.

TABLE V

Comparison of Special Spots with Whole Series

Spot No.	Circumfaculae K_3	Faculae K_3	Penumbrae K_3	Umbrae Bright Line
6771.........	3933.668	3933.668	3933.673	3933.688
6772.........	.666	.670	.676	.666
6774.........	.661	.670	.678	.670
6786.........	.682	.685	.681	.697
6787.........	.677	.687	.681	.693
6788.........	.677	.676	.682	.684
Whole series..	.680	.679	.680	.682

It will be noticed that in the case of these three spots at their first apparition the state of the absorbing vapor was exceptional over the faculae as well as over the circumfacular regions, in neither instance showing any indications of a circulation between the two regions; and that in the case of two spots the calcium vapor was not descending over the umbrae, while on their second apparition all three were in agreement with the majority of the spots observed in showing a descent of the calcium.

The results of this investigation of twenty-six circumfacular regions appear to differ from those obtained by M. Deslandres as reported in the *Annales de l'Observatoire de Meudon*, Tome IV, pp. 75–79. Measurements were carried out at Meudon over the faculae and their immediate surroundings upon plates taken with the *spectro-enregistreur des vitesses*.

Les mesures ont porté seulement sur la raie centrale K_3, qui est nette et bien délimitée sur le disque entier; on a laissé de côté, au moins provisoirement,

> la raie K_2, dont les composantes ne se prêtent pas toujours à un pointé précis. Les vitesses sont seulement relatives, car on a adopté pour déplacement zéro la moyenne des déplacements de tous les points de l'image. Or sur la facule, dans la grande majorité des cas, ... les vitesses sont descendantes, et tout autour ascendantes. Ce fait expérimental a été vérifié sur une dizaine des facules.

And again, page 93:

> Cette conclusion, avant d'être acceptée comme absolument définitive, devra être appuyée sur des mesures plus nombreuses de vitesse radiale, faites non seulement au centre du Soleil, òu les vitesses verticales seules interviennent, mais à une certaine distance de ce centre; ce qui permettrait de reconnaître les vitesses parallèles à la surface. Dès, à présent, on peut affirmer qu'elle est extrêmement probable.

The apparent disagreement in the results of the two investigations may possibly be referred to the different types of faculae studied in the two cases. In the present work all the faculae are large and in the immediate neighborhood of spots. The case shown in the Meudon *Annales* is that of a small facula unconnected with any spot. Then, too, the Meudon measurements are relative, the zero of displacement being the mean of all the displacements. In the present investigation the second slit was wide enough to admit the two iron standards, one on each side of K_3, from which the absolute wave-length of the displaced K_3 line was determined and through which the measurements were referred to the wave-length of the K line in the arc. From the adoption of the arbitrary zero in the former case it may be that the rise of the absorbing vapor in the circumfacular regions is only apparent, and that it is really descending in both regions, which would bring the results into nearer agreement. In view of the bearing of the results upon hypotheses relative to systems of circulation in the solar atmosphere the investigations at Mount Wilson will be extended to include large and small faculae and their immediate surroundings in cases where there are no associated spots.

RADIAL AND ROTATIONAL MOTION OF THE CALCIUM VAPOR OVER THE PENUMBRAE OF SPOTS

Radial movement of the reversing layer in sun-spots, showing an outflow with a velocity of one or two kilometers per second, was announced by Evershed in 1909.[1] In a subsequent paper, under the heading "Radial Motion in the Higher Chromosphere,"[2] he writes as follows:

> I have said that the spectrum-lines are universally found to be displaced toward the red on the side of the penumbrae nearest the limb, and to the violet on the opposite side, thus indicating an outward movement. There are, however, two notable exceptions among the host of absorption lines in the solar spectrum. The central absorption lines, known as H_3 and K_3 (possibly also the underlying emission-lines H_2 and K_2) when clearly defined in the penumbrae, are displaced in exactly the opposite sense in every case I have examined, that is, towards the violet on the limb side of the spot, thus indicating an indraught of the calcium vapour of the higher chromosphere. . . . . It would seem natural to suppose that the calcium vapour is drawn downwards as well as inwards, and I cannot at present say whether this is so or not, although some of my measures indicate such a downdraught.

In the same paper Mr. Evershed considers the question of a spiral motion of the outflowing vapors of the reversing layer. He finds in the case of five spots a mean rotational movement of 0.35 km per second and a radial motion of about 2 km per second, by combining which he gets a spiral movement opposite in direction in the two hemispheres. In the present investigation of the movement of the chromospheric calcium vapor to which the origin of the lines K_2 and K_3 is referred, plates were taken in the case of four spots with the slit of the spectrograph across the centers of the umbrae and *parallel* to the radius of the solar image passing through the spot. The measurements were carried out upon both the K_2 and the K_3 lines over the limb edges and center edges of the penumbrae of the spot as shown in Table VI.

The typical appearance of the absorption line K_3 was that of a sinuous curve showing no abrupt change in direction at the outer limit of the penumbrae, but bending gradually back into the undisplaced line, as indicated by Plate III (*b*). Three of the four spots were followed from the east to the west limb; one was observed only near the east limb; but in every instance the wave-length on the edge of the penumbra toward the center was greater than on the edge toward the limb. In the former case the wave-length was longer than the corresponding wave-length in the arc, and in the latter the wave-length was always shorter than in the arc. The mean line-of-sight components for the four spots and the corresponding motions along the solar surface found by dividing by the sine of the angular distance from the center are given in Table VII.

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[1] Evershed, *Monthly Notices of the Royal Astronomical Society*, **69**, 454, 1909.

[2] *Ibid.*, **70**, 218, 1910.

TABLE VI

THE K_2 AND K_3 LINES OF CALCIUM OVER THE PENUMBRAE OF ECCENTRIC SPOTS

Slit parallel to the radius through the spot

SPOT	PLATE	DATE	LIMB EDGE		CENTER EDGE		REMARKS
			K_2	K_3	K_2	K_3	
No. 6869 On C.M. July 18.6, 1910	173c	1910 July 15	3933.650	.658	3933.673	.683	Line curved. 29 mm from East limb Return of 6862
No. 6874 On C.M. Aug. 9.5, 1910	182c	Aug. 4	.660	.637	.673	.668	Line curved. Spot 6 mm from East limb 1st apparition. Returned as 6880
	185c	Aug. 5	.653	.651	.702	.698	Line strongly curved. 17 mm from East limb
	187c	Aug. 6	.656	.651	.687	.690	Line curved. 30 mm from East limb
	195c	Aug. 9	.666	.661	.687	.687	On central meridian. 59 mm from South limb
	199c	Aug. 11	.664	.659	.662	.680	Line curved. 35 mm from West limb
	201c	Aug. 12	.651	.638	.680	.683	Line curved. 23 mm from West limb
			3933.658	.650	.680	.683	
No. 6880 On C.M. Sept. 5.8, 1910	219c	Aug. 31	.632	.637	.652	.669	Line sharply curved. 4 mm from East limb. Return of 6874
	221c	Sept. 1	.639	.639	.668	.668	Line curved. 12 mm from East limb
	223c	Sept. 8	.631	.624	.670	.686	Line strongly curved. 25 mm from West limb
	225c	Sept. 9	.633	.625	.681	.688	Line strongly curved. 15 mm from West limb
			3933.634	.631	.668	.678	
No. 6886 On C.M. Sept. 26.9, 1910	237c	Sept. 21	.645	.635	.665	.685	Line curved. 5 mm from East limb
	249c	Sept. 22	.649	.639	.686	.719	Line strongly curved. 13 mm from East limb
	255c	Sept. 24	.661	.654	.665	.693	Line curved. 40 mm from East limb
	256c	Sept. 26	.655	.653	.666	.687	
	261c	Oct. 1	.660	.640	.684	.702	Line curved. 8 mm from West limb
			3933.654	.644	.673	.697	

This gives an average horizontal velocity of 2.0 km per second for the absorbing vapor and of 1.24 km per second for the emitting vapor on each side of the spot. For the absorbing vapor the mean result corresponds closely with the mean found by Mr. Evershed, namely 1.83 km per second. The results for the K_2 line are of less weight owing to the greater uncertainties in the measurement; but it is an interesting fact that the mean is decidedly less than in the case of the absorbing vapor, that every measurement points in the same direction, and that a similar difference appears, as will be seen later, in the measurements when the slit was perpendicular to the radius of the solar image passing through the spot. The data for the seven spots on which observations were obtained with the slit *perpendicular* to the radius are given in Table VIII.

TABLE VII

LINE-OF-SIGHT COMPONENTS AND MOTIONS ALONG SOLAR SURFACE

Spot No.	Unreduced		Reduced	
	K_2	K_3	K_2	K_3
6869	1.75 km	1.91 km	2.59 km	2.75 km
6874	1.68	2.59	2.29	3.51
6880	2.59	3.12	3.20	4.42
6886	1.45	4.04	1.83	5.33
Relative motion	1.87	2.91	2.48	4.00
On each side	0.94	1.46	1.24	2.00

With a slit normal to the radius vector through the spot the radial flow of the vapor would produce no Doppler effect, but the rotational, or spiral movement of the vapor would displace the line on one side of the spot to the red and on the opposite side to the violet. After the spot passes the meridian the displacements on the two edges of the spot would be reversed; if the direction of rotation is such that the north edge is approaching when the spot is east of the meridian the north edge will be receding when the spot is west of the meridian. This was distinctly the condition shown by spot 6577 and its return as 6592, and also by spot 6874. Of the seven spots observed, counting each apparition, five showed relative displacements of the K_2 and the K_3 lines for the north and south edges. On Plate III (*c*) is shown an enlarged reproduction of a limited portion of the spectrum of spot 6874 with the slit at right angles to the radius vector. On the original negative the displacements on the opposite sides of the spot are very distinctly visible. By holding the reproduction on the level of the eye and looking along the line the relative displacements may be seen.

TABLE VIII

THE K_2 AND K_3 LINES OF CALCIUM OVER THE PENUMBRAE OF ECCENTRIC SPOTS

Slit perpendicular to the radius through the spot

SPOT	PLATE	DATE	I			II			REMARKS
			K_2	K_3	Edge	K_2	K_3	Edge	
No. 6577 On C.M. Dec. 8.3, 1908	144	1908 Dec. 13	3933.649	.639	N.	3933.711	.706	S.	At West limb. Returned as 6952
			.651	.648	N.	.706	.714	S.	
No. 6592 On C.M. Jan. 4.7, 1909	183	Dec. 30	.649	.635	S.	.677	.677	N.	At East limb. Return of 6577
			.659	.645	S.	.664	.666	N.	
			3933.652	.642		3933.690	.691		
No. 6610 On C.M. Feb. 2.2, 1910	237	1909 Jan. 28	.676	.683	N.	.686	.689	S.	8 mm from East limb
			.670	.663	N.	.669	.683	S.	Only observation
			.682	.676	N.	.680	.694	S.	
			.677	.671	N.	.684	.704	S.	
			3933.676	.673		3933.680	.693		
No. 6869 On C.M. July 18.6, 1910	173*c*	1910 July 15	.664	.656	N.	.691	.683	S.	29 mm from East limb
			.667	.660	N.	.681	.694	S.	Only observation
			3933.666	.658		3933.686	.689		
No. 6874 On C.M. Aug. 9.5, 1910	182*c*	Aug. 4	.668	.683	N.	.666	.650	S.	6 mm from East limb. Line curved. Returned as 6880
			.670	.685	N.	.671	.663	S.	
	185*c*	Aug. 5	.666	.683	N.	.661	.645	S.	17 mm from East limb. Line curved
	195*c*	Aug. 9	.676	.680	E.	.674	.672	W.	On central meridian 30 mm South of center
	199*c*	Aug. 11	.691	.692	S.	.664	.666	N.	35 mm from West Limb. Line curved
	210*c*	Aug. 14	.669	.672	S.	.652	.642	N.	5 mm from West limb. Line curved
			.672	.684	S.	.651	.638	N.	
			3933.673	.683		3933.663	.654		
No. 6880 On C.M. Sept. 5.8, 1910	219*c*	Aug. 31	.648	.652	N.	.659	.667	S.	4 mm from East limb. Return of 6874
	221*c*	Sept. 1	.656	.660	N.	.661	.661	S.	12 mm from East limb
	223*c*	Sept. 8	.681	.682	S.	.679	.681	N.	25 mm from West limb
			.671	.683	S.	.663	.667	N.	
			3933.666	.667		3933.664	.669		
No. 6886 On C.M. Sept.26.9, 1910	237*c*	Sept. 21	.654	.666	N.	.663	.668	S.	5 mm from East limb
	249*c*	Sept. 22	.673	.677	N.	.672	.679	S.	13 mm from East limb
	261*c*	Oct. 1	.684	.700	S.	.681	.686	N.	8 mm from West limb
			3933.670	.681		3933.672	.678		

In the case of spot 6577 when it was near the west limb the north edge of the penumbrae gave the shorter wave-length. When it appeared at the east limb as 6592 the south edge gave the shorter wave-length. Considering the relative displacements at the two edges of the penumbrae as due to motions in the line of sight it follows that when the spot was east of the meridian the penumbral calcium vapor was approaching on the south side and receding on the north side; and when the spot was west of the meridian the penumbral calcium vapor was approaching on the north side and receding on the south side—indicating in both instances a counter-clockwise rotation for this spot which was situated in north latitude. In the case of spot 6874 observed during its passage from the east to the west limb, the rotation was in the same direction, but the spot was situated in south latitude. That these displacements are not due to an easterly and westerly drift on the north and south sides of the spot is shown by an observation on spot 6874 when on the meridian and south of the center by approximately one-third of the solar radius. In this position of the spot with the slit at right angles to the radius the displacements indicated approach of the penumbral vapor on the west side and recession on the east side, thus pointing to a true rotary movement. Of the three spots in the northern hemisphere two, 6610 and 6609, show a clockwise rotation; one, 6577, and its return, 6592, show a counter-clockwise rotation. We have then the two cases: spots in the same

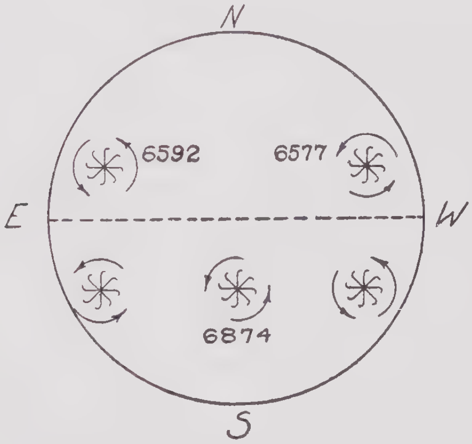

Fig. 1.—Spots in two hemispheres with same direction of rotation

hemisphere showing opposite rotations and spots in the two hemispheres showing rotation in the same direction. In reference to his own observations Mr. Evershed says:[1]

> The opposite movement in the two hemispheres, although clearly shown in five instances, may not be an invariable rule. Referring to the magnetic field in spots, Professor Hale states that "although the larger spots in the northern and southern hemispheres of the Sun are usually found to be of opposite polarity, it frequently happens that spots of opposite polarity occur in the same hemisphere, sometimes in the same spot group."[2] One would expect, therefore, if the rotation movement bears a causal relation to the magnetic field, to find occasional instances of spots showing a clockwise rotation in the north, or vice versa.

Two of the seven spots observed, 6880 and 6886, showed no evidence of rotational motion. One of the two, 6880, was the return of 6874, which on its first apparition showed such motion unmistakably. The means of the line-of-sight components of the rotational motion and the corresponding velocities along the solar surface found by dividing by the sine of the angular distance from the center are given in Table IX.

TABLE IX

LINE-OF-SIGHT COMPONENTS AND MOTIONS ALONG SOLAR SURFACE

SPOT NO.	UNREDUCED		REDUCED	
	K_2	K_3	K_2	K_3
6577....................	4.50 km	5.11 km	4.50 km	5.11 km
6592....................	1.30	2.36	1.45	2.59
6610....................	0.30	1.52	0.38	1.67
6869....................	1.52	2.36	2.29	3.58
6874....................	0.76	2.21	1.19	2.92
Relative motion..........	1.68	2.71	1.96	3.17
On each side...........	0.84	1.36	0.98	1.59

This gives an average horizontal rotational velocity of 1.59 km per second for the absorbing vapor and of 0.98 km per second for the emitting vapor on each side of the spot. The combination of the rotational movement with the inflow and downward movement gives a real vortical motion inward for the calcium vapor in the case of these four spots.

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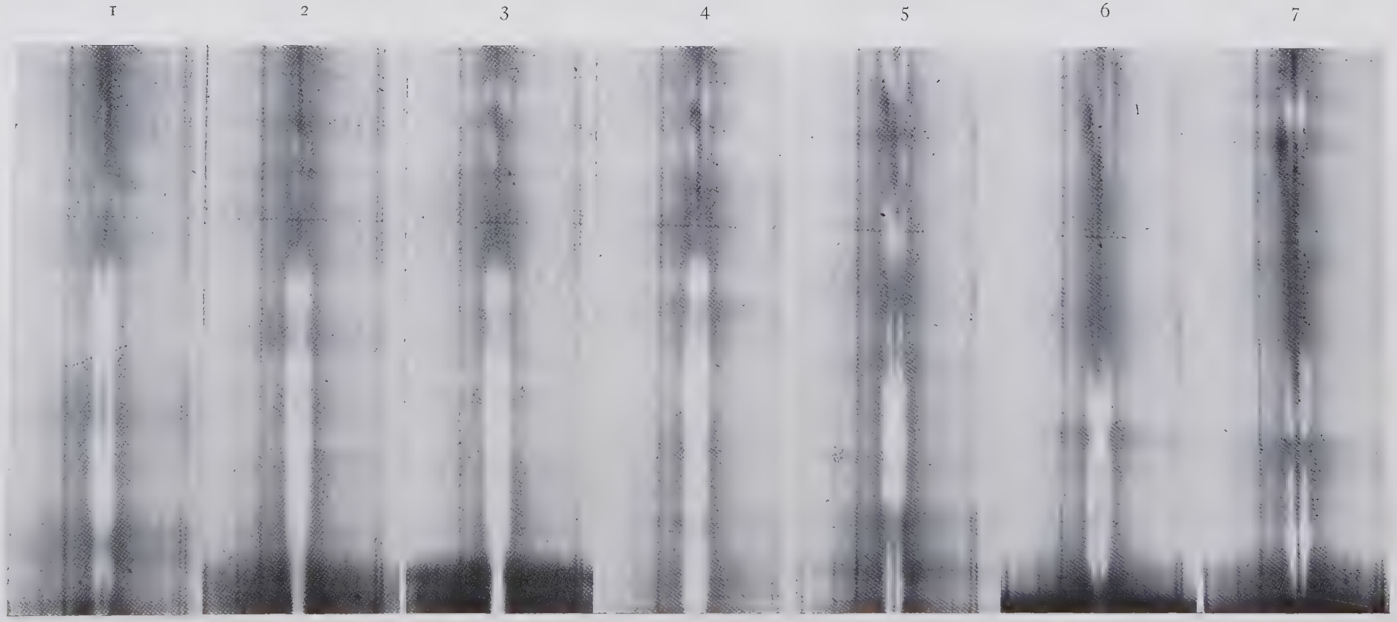
[1] Evershed, *Monthly Notices of the Royal Astronomical Society*, **70**, 224, 1910.

[2] Hale, *Publications of the Astronomical Society of the Pacific*, **21**, 205, 1909.

PLATE IV



The K Line of Calcium at 2 mm Intervals in the Neighborhood of a Detached Moving Mass of Vapor

Enlargement: 5 times from original negative with 18-foot spectrograph and Snow telescope. 1909, January 29

Exposures 1, 2, Normal condition

Exposures 5, 6, Abnormal absorption line to the violet of and distinct from K_3

PROMINENCES IN PROJECTION

Occasionally spectrum plates have been obtained in which the K absorption line has shown extraordinary appearances. These have been obtained at various times, and sometimes by successive exposures near the same point of the solar surface, so that the reality of the appearances is well established and the phenomena which they represent must be of quite frequent occurrence in the sun. The data for the plates showing such peculiarities are given in Table X.

The characteristic appearance in each case upon which the present interpretation is based is the undisturbed condition of the absorption line K_3. This occupies its usual position, as shown by its wave-length agreeing with the normal value for this part of the disk, and is bounded on the red and violet edges by the emission line K_2. In some cases the violet component of K_2 shows a narrow absorption line superposed upon it through a distance of some millimeters. In other instances there is a broad absorption line on the violet side of the emission line. The approximate wave-length of this abnormal line shows a high ascending velocity in the vapor to which it is due. From the fact that the ordinary absorption line is undisturbed it appears that the phenomena here manifesting themselves by the displaced absorption line originate in great masses of calcium vapor having no direct connection with those levels of the solar atmosphere where the ordinary absorption line is produced and moving independently of that part of the atmosphere. That is, they are detached masses of vapor, such as prominences on the solar hemisphere turned earthward would present. The phenomenon bears a certain analogy to that observed by Frost and by Slipher in the spectra of spectroscopic binaries in which the H and K lines were undisplaced, and of which the suggested interpretations are an extended atmosphere of calcium surrounding the system or detached masses of calcium vapor in space. Plate IV is a reproduction of a photograph taken with 2 mm steps over such a moving mass. It is possible to see in the upper third of the reproduction, on exposures 5, 6, and 7, the characteristics referred to: the undisturbed K_3 line, the two components of the K_2 line, and the absorption line displaced to

TABLE X

ABNORMAL K LINE OVER SPECIAL REGIONS

Plate	Date	Normal K_3 Line	Abnormal K Line	Velocity of Ascent	Remarks
	1909			km	
216......	Jan. 19	3933.675	3933.464	15.5	V K_2 double over a region of the solar surface 50,000 km in extent. K_3 undisturbed. Bounded by the bright components of K_2. 50 mm from the East limb
226......	Jan. 20	.680	.470	15.0	V K_2 double over a region 100,000 km in extent. K_3 regular and undisplaced. 50 mm from East limb
247......	Jan. 29	.683	....	....	2 mm steps from east to west. Over dark hydrogen flocculus north of spot 6608. Exposure 2, normal conditions
247......	Jan. 29	.679	....	....	Exposure 3. R K_2 partially washed out on red edge. V K_2 broad. K_3 sharply bounded on V K_2 side. Faintly bounded by R K_2
247......	Jan. 29	.679	.484	13.9	Exposure 4. V K_2 broad. Divided by absorption line. K_3 undisturbed and bounded by the two components of K_2
247......	Jan. 29	.681	.412	19.4	Exposure 5. K_3 undisturbed. Bounded by K_2 on both edges. Broad dark line to the violet of V K_2
247......	Jan. 29	.678	.349	24.2	Exposure 6. K_3 undisturbed. Bounded by K_2. Broad dark line to violet of V K_2
247......	Jan. 29	.681	.378	22.0	Exposure 7. K_3 undisturbed. Extraordinary absorption line similar to exposure 6.
257......	Jan. 30	.676	.456	16.1	Exposure 1. V K_2 double over region of solar surface. 15,000 km in extent. K_3 undisturbed. Bounded by K_2 on each edge
257......	Jan. 30	.670	.467	15.2	Exposure 2. 15,000 km west of Exposure 1. V K_2 double over region 35,000 km in extent. K_3 undisturbed. Bounded by K_2 on both edges
276......	Feb. 22	.684	.466	15.3	V K_2 double over a region 80,000 km in extent. K_3 undisturbed. At center. Time 10 A.M.
286......	Feb. 22	.676	.460	15.8	Same region as in No. 276, but 4 hours later

the violet. A fine example of this effect is shown in the beautiful reproduction, Plate 46, of the Meudon *Annales*, Tome IV. Under the title "Sur un filament extraordinaire,"[1] MM. Deslandres, d'Azambuja, and Burson report on this interesting case in which the displacements indicated vertical velocities exceeding 100 km per second. The phenomenon was of short duration, ending an hour and a half after the maximum velocity had been gained. It was not attributed to a prominence viewed in projection against the disk, but otherwise the interpretation,

> Tout se passe comme si, la couche K_3 restant à peu près dans son état ordinaire, une grande masse de gaz au-dessus, distincte de la première, s'élevait irrégulièrement à de grandes vitesses,

is the same as that given here.

It seems more than probable that the dark flocculi or *filaments* are closely connected with prominences when the remarkable Plates 43 and 45, Tome IV of the Meudon *Annales*, are examined. These reproduce K_3 spectroheliograms taken four days apart, upon which a long, dark flocculus, or chain of such, extends across the southern hemisphere of the sun. On Plate 43, where the dark flocculus reaches the east limb, it appears to blend into a large prominence, and at the west limb at the point touched by the flocculus, a small prominence is shown. On Plate 45, taken four days later, the flocculus has advanced from the east limb and the associated prominence has disappeared, while at the west limb the prominence has increased in height and appears still on the line of the dark flocculus. The whole appearance is as if the dark flocculus were a mass of calcium vapor high above the chromosphere, revealing itself on the disk by absorption and at the east and west limbs as prominences. Such masses of calcium vapor would be expected, under this point of view, to show as they do at times the enormous upward velocities obtained in the case of prominences. As the projected masses settle back again the motion would be slower. Measurements of the K_3 line over such a dark flocculus appearing on the $H\alpha$ spectroheliogram of August 4, 1910, gives over the flocculus λ 3933.681, and around the flocculus λ 3933.675, indicating a downward movement in both cases which was slightly greater over the region of greater absorption. The same point of view is held by Mr. Michie Smith, who states that these dark calcium flocculi when photographed near the limb are found to agree in position with the prominences.[1]

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[1] *Comptes Rendus*, **150**, 1638, 1910.

Mr. Evershed[2] considers the very conspicuous dark flocculus shown on certain H_2 spectroheliograms taken at Kodaikânal, Feb.–Apr. 1910, as due to absorption produced by the extensive prominence then transiting the sun's disk, and says:

> When these dark markings are seen extending to the sun's limb they are found almost invariably to end in a prominence, but the latter in many cases are somewhat insignificant in height.

The detailed spectrographic study of such regions of absorption is a part of the program at Mount Wilson.

DISCUSSION

The evidence for and against general or local systems of circulation of the chromospheric calcium vapor deduced from the data of this paper may be considered from the point of view of the absorbing and emitting layers separately and together. In the case of the absorbing vapor the wave-length measurements over possibly related regions are:

At the center	3933.680 (63)[3]
Circumfacular regions	.678 (134)
Flocculi	.679 (176)
Penumbrae	.681 (120)
Umbrae	.681 (11)
In the arc	.667[4]

The most striking feature of the assembled data is the remarkable agreement of the separate means with the general mean 3933.679 from five hundred separate exposures. It appears that on the whole the high-level calcium vapor of the chromosphere is descending over these different regions of the solar surface with a surprisingly uniform velocity on the average. In seeking for the source of supply we may look to outer space as Professor Newall has suggested, or to the inner regions of the sun. In speaking of the possibility of attributing the main characteristic spectroscopic phenomena of the sun to matter constantly streaming in from without Professor Newall[1] says:

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 25, 7; *Astrophysical Journal*, **27**, 225, 1908.

[2] *Astrophysical Journal*, **33**, 6, 1911.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 48, 41, 1910; *Astrophysical Journal*, **32**, 76, 1910.

[4] *Contributions from the Mount Wilson Solar Observatory*, No. 44, 10, 1910; *Astrophysical Journal*, **31**, 152, 1910.

> We may divide the attracted matter into three categories: (I) molar matter, in masses large enough to be drawn in in spite of light-pressure, having diameters longer than about 2½ times the wave-length of light; (II) molecular matter, in masses small enough to escape, in virtue of the diffractional effects, the repulsion of light, having diameters less than about one-tenth of the wave-length of light; and (III) light-driven matter, in masses intermediate between molar matter and molecular matter, and subject to the repulsion of light.
>
> The reversing layer of the Sun is provided by molecular matter, constantly streaming across what we may call a critical envelope concentric with the Sun, and probably is in a slightly modified state of radiative equilibrium. The constant flux of matter here involved is provided by those constituents of the planetary whirl of molecular matter circulating round the Sun, which are directed inwards upon the Sun in virtue of properly directed collisions.

If there were no evidence of any source of supply from the inner regions of the sun, the practical agreement of the mean velocities of the descent of the absorbing layer of calcium over such diverse regions of the solar surface as those over which the above measurements were made might well be adduced as tending to support the hypothesis of a constant influx from outer space. The rotation of this absorbing layer shows a small polar retardation and a high equatorial velocity relative to the reversing layer, but still an organized rotation of low value compared to planetary velocities. There is evidence, however, that calcium vapor is rising from the interior over the general surface of the sun and over particular regions. As previously quoted in this paper from *Contribution* No. 48 the measurements of the wave-length of the K_2 line of calcium due to emitting vapor was found to be 3933.641 Å over the general surface of the sun as against 3933.667 Å in the arc, indicating a mean upward velocity of 1.97 km per second. This vast ascending mass of calcium vapor would seem to be sufficient for the continual renewal of the supply, though perhaps in a less simple manner than the inflow from outer space. Over limited but still extensive areas of the solar surface great masses of relatively cool calcium vapor are ascending with very high velocity. These have been attributed to prominences seen in projection. These masses of vapor must diffuse laterally and eventually return to the solar surface under the action of gravitation, being free from the effects of light-pressure owing to their molecular condition. The supply from this source, probably having its origin in eruptions of much denser vapor from the interior, would hardly account for the layer of absorbing vapor enveloping the whole sun. This finds a sufficient and more probable supply in the vapor producing the K_2 line of calcium which is ascending over the general surface.

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[1] Newall, Presidential Address, *Monthly Notices of the Royal Astronomical Society*, **69**, 343, 1909.

The quantitative data with a bearing upon a circulation of the calcium vapor shown by measurements of the K_2 line are the wave-lengths of this line over particular regions as shown below:

Over general surface.......	3933.641 (20)[1]
Over flocculi.	.664 (175)
Over penumbrae..........	.665 (120)
Over umbrae.............	.682 (141)
In the arc................	.667

This shows a rise of emitting vapor over the general surface with a velocity of 1.97 km per second and a descent of this vapor in the umbrae of spots with a velocity of 1.3 km per second, a total range of 3.27 km per second. The condition over the flocculi indicated by these measures is an intermediate one, possibly, on the whole, one of slow ascent. Taken in connection with the inflow shown in Table VII the evidence for a system of circulation of the emitting vapor is quite complete, in which the supply of vapor descending in the umbrae of spots is that rising mainly from the immediate surroundings of the flocculi and their peripheral portions and flowing toward the umbrae where it is drawn suddenly and rapidly inward.

Attention has been called to the difference between the velocities of inflow and rotation obtained from wave-lengths of the K_2 and K_3 line. The results from Tables VII and IX are:

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 48, 21, 1910; *Astrophysical Journal*, **32**, 56, 1910.

	K_2	K_3
Inflow........	1.24 km	2.00 km
Rotation......	0.98	1.59

Everything occurs as though the disturbance begins in the upper layer of the chromosphere and works down into the emitting layer, to which it communicates a motion of inflow and rotation, the lower stratum always lagging behind the upper. In the great majority of cases the K line over the umbrae is bright and single, but on a few plates taken even when the seeing was excellent the absorption line K_3 is present, while on later plates of the same spot it had disappeared. In such a case the presence of the absorption line cannot be due to photospheric light falling upon the slit of the spectrograph. The absorption line appears to be at times a real spot phenomenon and there is some evidence that it belongs to the earlier life history of a spot.

Some light is thrown upon the bright reversal of the K line over the umbrae of spots by comparing the relative intensities of the umbral line and the K_2 and K_3 components over the penumbrae. For this purpose there was at hand the photometer devised by Hartmann[1] for the measurement of the intensities of photographically blackened surfaces. This enables one to isolate an extremely small portion of the surface and to match its intensity against the photographically produced wedge. The measurements are given in Table XI, in divisions of the wedge-scale, which increase with increasing density in the negative.

A striking result is the relatively weak intensity of the bright umbral line compared with that of the K_2 and K_3 components immediately outside the umbra. Under ordinary visual examination of the negatives one gets the impression that the umbral line is much brighter than K_3 and almost equal in brightness to K_2 while in fact it is slightly less bright than K_3 on the average (Plate III, *a*). The dark background of the umbra brings the line into high relief, just as in the laboratory experiments on the sodium reversal the line appears to decrease in brightness on passing from the dark background to the intense continuous background of the arc. Since the temperature of the spot umbra is lower than that of the surroundings, the bright umbral line is probably produced by the same vapor as that to which the K_2 line is due, there being a continuous flux of the vapor into the umbra. The line is narrower and less bright than the K_2 line over the flocculi and penumbra, as would naturally follow from the diminished pressure and lower temperature obtaining at the center of the spot vortex. The resulting fall in the temperature of the absorbing vapor in the spot umbrae would reduce its radiation below that of the vapor to which the umbral line is due, as the bright line is frequently double the width of the K_3 line, and not always less intense as may be seen from the last three lines of Table XI. Therefore, it does not seem probable that the upper layer of calcium plays an important rôle in the production of the reversal. The absence of the K_3 line over the umbrae may be due to the diminished quantity of the absorbing vapor which was earlier drawn inward, while that supplied by the lateral inflow mainly descends in the region of the penumbrae and fails to reach the umbral region in large quantity during periods of rapid downdraught.

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[1] *Astrophysical Journal*, **10**, 321, 1899.

TABLE XI

Relative Intensities of the Components of the K Line

Over Umbrae			Over Penumbrae	
Reversal	V K_1	R K_1	K_2	K_3
40.4	28.1	27.5	45.4	43.2
35.6	25.7	26.3	45.6	41.2
48.1	37.2	36.8	58.9	53.1
47.0	36.0	35.1	55.2	48.0
41.1	28.2	28.3	46.3	41.2
44.4	29.5	29.6	57.1	....
44.9	28.5	28.3	46.2	44.0
49.6	30.2	29.7	56.0	48.4
50.9	47.3	47.0	66.4	50.3
44.7	32.3	32.1	53.0	46.5

Plate III (*a*) reproduces the typical condition over spot umbrae, though in many cases the reversal is relatively more intense than here shown. The curve (*c*) in Fig. 2 is drawn from the data in Table XI and represents the K line over the umbra of a spot. The widths of the K_2 and K_3 lines in Fig. 2 are drawn to scale and show the relative widths under the different conditions to which the curves refer, but the width of the K_1 line is only suggested. The ordinates of the curves reproduce the relative intensities of all the components in terms of the wedge-scale. The intensities of the absorption line on the two sides of the reversal as shown by these measurements are practically equal, individually, and on the average. Jewell[1] found that:

> The absorption toward the red from the reversal was considerably darker and broader than toward the violet, thus giving evidence of considerable relative velocity between the emission line and the broad absorption line or shading.

The present measurements show that the bright umbral line is shifted to the red, which would tend to cause the absorption in the K line to be more conspicuous toward the violet. A compensation might result from the displacement of the center of gravity of the K_1 line also to the red owing to the greater pressure under which the line is produced.

The inflow of the calcium vapor and the downdraught in the umbrae appear to be the usual condition of the spot, but the penumbral or extra-penumbral vortex is not developed around every spot, nor does it always persist in the case of a given spot when once developed. This is in harmony with the visual observations of Secchi, who considered the vortex an exceptional case:

> Si cela arrive quelquefois, c'est assez rare, car, sur trois cents taches et plus qu'on observe dans le cours d'une année, il y en a sept ou huit seulement qui présentent d'une manière bien tranchée la structure spirale qui devrait caractériser les tourbillons. . . . . Non seulement les taches ne présentent pas toutes la forme de tourbillons, mais, de plus, cette forme, lorsqu'elle existe, ne persiste pas plus d'un jour ou deux, tandis que les taches elles-mêmes peuvent subsister longtemps encore après avoir perdu la forme spirale.[2]

The spiral structure is not shown around all spots on the $H\alpha$ spectroheliograms, though the spots themselves are magnetic fields as evidenced by the Zeeman effect. It is probable that in many

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[1] *Astrophysical Journal*, **3**, 105, 1896.

[2] Secchi, *Le Soleil*, Part I, p. 89.

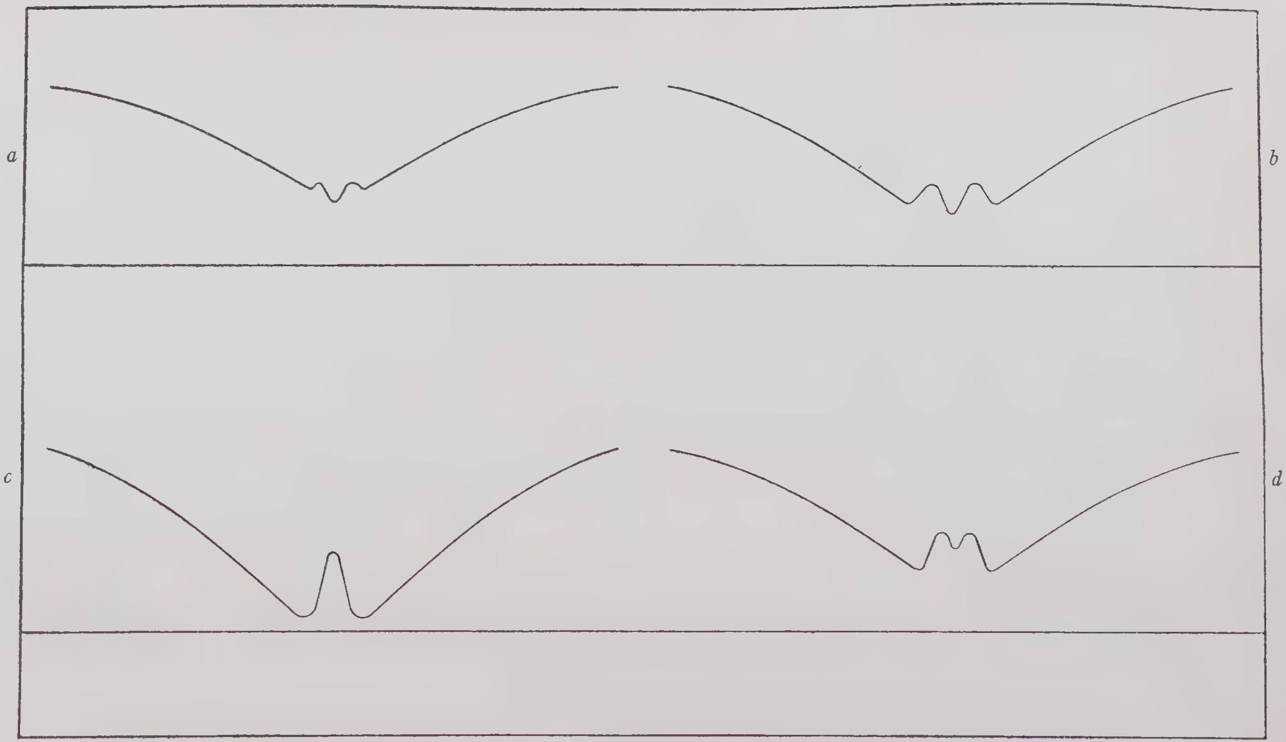

FIG. 2.—Relative intensities of the components of the K line of calcium

a, At the center of the solar disk
b, At the sun's limb
c, Over sun-spot umbrae
d, Over flocculi

instances the region throughout which the vortex is strongly developed does not extend very far outside the umbra, and the surrounding gaseous masses are not sufficiently involved to be arranged in stream-lines. It is surprising that, in view of the spectroscopic evidence of the inflow and downdraught of the calcium vapor, spectroheliograms taken with the H and K lines do not show more indication of stream-lines which are sometimes such marked features over vast areas of the *Hα* spectroheliograms. This may be due to calcium vapor being present in broader and more continuous masses over the flocculi, and being more uniformly distributed around spots than the hydrogen. If an electro-magnetic instead of a hydrodynamic cause be assumed for the line-of-force structure on *Hα* images, a suggestion made by M. Deslandres may be the key to the explanation:

> Chaque ion solaire mobile subit le champ électrostatique et électromagnétique de tous les autres. Comme l'effet n'est pas le même pour les atomes des masses différentes, on aurait là une explication des différences que présentent les images du calcium et d'hydrogène dans l'atmosphère solaire.[1]

Stream-line structure does occasionally occur on H_2 spectroheliograms according to both Hale and Evershed. In speaking of this Hale says:

> We have seen, however, that apparent lines of force having about the same curvature as the dark *Hα* flocculi are frequently shown by H_2 between spots of opposite polarity, though this line fails to give most of the finer details of the *Hα* structure. The difference may be due in large part to the greater effect of convection currents at the H_2 level.[2]

And Evershed writes:

> In good spectroheliograph plates of the calcium flocculi the regions of the penumbrae in quiet spots often show radial stream-lines and these are sometimes curved. In general, however, the more brilliant masses of flocculi of the surrounding region show no tendency to either a radial or a spiral structure.[3]

RELATIVE INTENSITIES OF THE K LINES

In the study of the conditions which produce the complex constitution of the H and K lines it appeared probable that a knowledge of the relative intensities of the components of the K line would be useful, and particularly the intensity of K_2 in comparison with the intensity of the continuous spectrum in the case of the very brilliant flocculi. For this purpose the Hartmann photometer was found very convenient and satisfactory.

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[1] *Comptes Rendus*, **150**, 72, 1910.

[2] *Publications of the Astronomical Society of the Pacific*, **22**, 77, 1910.

[3] *Monthly Notices of the Royal Astronomical Society*, **70**, 224, 1910.

One of the most striking appearances in a series of exposures extending from the limb to the center of the sun in which the exposure-times are such as to give equal intensities for the continuous spectrum is the great intensity of the K_2 components at the limb, and their gradually decreasing intensity with increasing distances from the limb. At the limb these components are very conspicuous, while at the center they are apparently very weak, except over flocculi, but still distinctly visible. Two typical plates were selected from a long series, upon which the intensity of the K_1, K_2, and K_3 lines was measured with the mean results in Table XII, which are expressed in divisions of the wedge-scale and represent the ordinary conditions at the center and limb of the sun.

TABLE XII

RELATIVE INTENSITIES OF THE K LINE AT LIMB AND CENTER

Plate	Position	K_1	K_2	K_3	K_2-K_1	K_2-K_3	K_1-K_3
329........	Center	54.1	54.9	50.6	0.8	4.3	3.5
462........	Limb	50.4	54.8	47.9	4.4	6.9	2.5

Two points revealed in obtaining this series of measurements are surprising, namely: the equal intensities of the K_2 line at the limb and center, and the difficulty of detecting with the photometer the difference between K_2 and K_1 at the center. When the lines are all in the field of view of the photometer, the K_2 line is distinctly seen and the dissymmetry of its components is clearly apparent, but when a small portion of the K_2 line is isolated by the photometer and settings of the wedge have been made for equality, it is very difficult to observe any change when the inner edge of the K_1 line is brought into the field of view. The results given in the table are the means of many settings. The apparent brightness of the K_2 line at the center is due largely but not entirely to contrast effect owing to the proximity of the strong absorption line K_3.

The increased intensity of the K_2 line at the limb is mainly apparent. The absolute intensities on these limb and center plates were practically equal, but the contrast effect at the limb was greatly increased by the greater strength of the absorption lines K_1 and K_3 between which the K_2 components lie. The effect is also enhanced by the greater width of the lines at the limb. In the cases of K_1 and K_3 the absorption at the limb, as would be expected from the greater effective depths of the absorbing layers, is greater than at the center for each line. But the increment in the case of K_1 exceeds that in the case of K_3, as they have become more nearly equal. At the center the K_2 line is just measurably brighter than the background produced by the K_1 line. At the limb the darkening of the background, particularly in the case of K_1, raises the K_2 line into relief without any great increase of its intensity. The results are shown graphically in Fig. 2, (*a*) at the center, (*b*) at the limb. The dissymmetry of the components of the emission line at the center is a marked feature, V K_2 being broader than R K_2. At the limb the components are equal in width and intensity. The curves are to scale and represent the relative widths of K_2 and K_3 and the relative intensities of all three components.

When the slit of the spectrograph crosses the very brilliant flocculi the density of the emission line K_2 appears to the eye, sometimes, to equal the density of the continuous spectrum. The photographic intensity of the spectrum decreases rapidly just beyond the K line due to absorption in the ultra-violet region by the glass of the lens. It was thought possible that the instrumental absorption might so reduce the intensity of the continuous spectrum on the violet side that a false result might be obtained if that alone were used. Comparison points were therefore taken on both sides of the K line at distances of about 12 Å with the following results expressed in the wedge-scale:

TABLE XIII

K_2 COMPARED WITH CONTINUOUS SPECTRUM

Plate	λ 3920	K_1	K_2	λ 3945	Continuous–K_2
197	69.5	39.3	59.2	70.7	10.9
267	59.5	28.6	48.5	60.9	11.7
296	57.6	39.2	51.2	58.2	6.7

In each case the intensity of the strong emission line was markedly less than that of the continuous spectrum even on the violet side. The usual calcium spectroheliogram is taken with H_2 or K_2, using one or both components, upon which the flocculi appear bright against the less intense background produced by the ordinary intensity of the line. The strength of the absorption line photographed with a long slit varies greatly along its length, becoming less intense as an absorption line when the slit crosses a flocculus, under which conditions it approaches the brightness of the emission line and may even disappear as an absorption line. The measurements in Table XIV were made at 2 mm steps along the line, including in the range of measurements two small flocculi.

TABLE XIV

INTENSITIES ALONG THE K_3 LINE

			Over Flocculus						Over Flocculus			
K_3	49.5	54.9	60.3	63.6	62.0	60.9	53.2	51.7	56.4	60.7	56.2	51.1
K_2	....	....	62.8	66.4	62.9	....	....	....	....	62.7	....	....

As seen, radiation has increased over the flocculi in both the K_2 and K_3 lines. The curve, (*d*), Fig. 2, shows the cross-section of the K line over such a flocculus. In comparing the ordinates of this curve with those of (*a*), it is seen that the radiation in the case of all three components has increased, the increase being the greatest for K_3. Spectroheliograms taken with the K_3 absorption line should show areas of great relative intensity corresponding to the flocculi shown on K_2 spectroheliograms; owing to the brightness of the K line over the umbrae, spots should not in general appear; and the dark flocculi, due to masses of absorbing vapor high above the chromosphere, should be much more conspicuous features than upon the K_2 spectroheliogram, since this cooler vapor, unless in very rapid motion, would greatly increase the absorption at the center of the K_3 line and affect the K_2 components in less degree. In speaking of the possible photography of the disk with the K_3 line Hale and Ellerman say:[1]

> If successful, photographs taken in this way will probably show the calcium prominences as dark regions projected upon the disk.

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[1] *Publications of the Yerkes Observatory*, 3, Part I, p. 19.

These are the appearances found by M. Deslandres in his skilful application of the spectroheliograph to work with the K_3 line:

> Cette couche supérieure, étudiée avec le calcium et l'hydrogène a comme caractères; l'extension jusqu'à elle des facules de la surface, mais avec des formes différentes, la disparition presque absolue des taches et l'apparition des lignes noires, souvent très longues, qui sont les filaments.[1]

THE EMISSION LINE K_2

There is complete consensus of opinion in the case of K_3 namely: that it is produced by absorption in the upper and cooler regions of the chromosphere. As to the bright reversals H_2 and K_2, Hale and Ellerman say:

> From a strict application of Kirchhoff's law it would appear that the calcium vapor in the lower chromosphere is actually hotter than the calcium vapor which lies above and below it. It seems improbable that the law can be rigorously applied in this case, and hence it may be necessary to attribute the strong radiation of the intermediate layer to causes other than temperature alone.[2]

Mr. Evershed speaks of the bright H_2 and K_2 lines as representing the emission of the relatively hot calcium vapor rising immediately above the ordinary faculae.

And Hale, in his *Stellar Evolution* (p. 86), says:

> The bright H and K lines, referred to in the last paragraph, were found in close association with the faculae, and it appeared probable that much of the highly heated calcium vapor, to which these bright lines are due, rises from the interior of the Sun through the faculae.

M. Deslandres considered the light of the chromosphere to have an electric origin and wrote of the brilliant flocculi overlying the faculae:

> Dans la chromosphère, les phénomènes électriques sont plus intenses au-dessus des points élevés de la surface.[3]

And later he has attributed the increased radiation over the bright regions to the compression produced by the descent of the vapors from the higher levels:

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[1] *Annales de l'Observatoire d'Astronomie Physique de Paris* (Meudon), **4**, 103, 1910.

[2] *Publications of the Yerkes Observatory*, **3**, Part I, p. 16.

[3] *Comptes Rendus*, **138**, 1377, 1904.

> En général, sur les parties brillantes, les déplacements sont vers le rouge; et la vapeur descend dans l'atmosphère. Comme alors elle se comprime et s'échauffe, l'augumentation de son éclat est naturelle.[1]

A somewhat analogous explanation of the bright reversals over the general disk was suggested by the writer,[2] namely, an increase of radiative power produced by the mutual interaction of the rising emitting vapor and the descending absorbing vapor, their relative velocity being found to be about 3 km per second. A small rise of temperature would probably be sufficient to account for the increased radiation, as Mr. King's work with the furnace has shown that the H and K lines are high-temperature lines in the sense that, with rise in temperature, they increase markedly in intensity in comparison with the arc lines, and without decided widening.[3] The temperatures available in Mr. King's experiments with the electric furnace did not exceed 3000° C. At solar temperatures the same increment of temperature would be less effective in increasing radiation, but that this characteristic of the H and K lines still obtains at solar temperatures is indicated by their great intensity in the sun as compared with that of λ 4226.9, which at low furnace temperatures is stronger than H and K. This explanation would have less force over the faculae where the calcium vapor has little if any upward velocity, while over these regions the radiation of the calcium vapor is the most intense.

A very different cause is assigned for the origin of the bright lines H_2 and K_2 by Professor Julius in his "Spectroheliographic Results Explained by Anomalous Dispersion."[4] This demands a density-gradient at right angles to the line of sight, which he finds in the cross-section of solar vortices:

> For it [the density] is a minimum in the axes of vortices; and the average direction of the whirl-cores, lying between the Earth and the central parts of the Sun in the surfaces of discontinuity, differs but little from our line of sight. The rays of the Sun thus reach us after having traveled a great distance along

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[1] *Annales de l'Observatoire d'Astronomie Physique de Paris* (Meudon), **4**, p. 77.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 48, 37–39; *Astrophysical Journal*, **32**, 72–74, 1910.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 32, 1908; *Astrophysical Journal*, **28**, 389, 1908.

[4] *Astrophysical Journal*, **21**, 278, 1905.

lines making small angles with the levels of slowest density variation in a lamellar, partly tubular, structure.

Accordingly, the bright lines H_2 and K_2 come from photospheric light of wave-length very near to that of the central absorption line, whose divergence has been changed to convergence by the tubular structure and thus reaches the earth with increased intensity. A serious difficulty involved in this explanation is that it demands that the axis of the tubular structure be always directed toward the earth. If the direction of the whirl-cores differs but little from our line of sight when they occur in the central portions of the sun, the direction must be nearly at right angles to our line of sight when they rise from the peripheral regions since they are approximately normal to the solar surface; but the spectroheliograph shows the flocculi near the sun's limb reduced in width as they would be by foreshortening if they were really bright surfaces. It is very easy to convince oneself by the examination of a series of daily spectroheliograms that the flocculi appear, as bright surfaces attached to the sun would appear in projection when carried across the line of sight by the sun's rotation.

It is evident that the bright reversal of the K line over the general disk and the increased intensity of the emission line K_2 over the facular region in comparison with the intensity over the general surface have not yet received a generally accepted explanation. An explanation of these reversals is here based upon the different radiation coefficients for the different parts of the line, and the molecular scattering of light. For the lower layer there is general agreement among solar spectroscopists, namely that the density of this layer is the basis for the great width of the line, and that for the central portion of the line at least, the absorption is complete. The temperature of this layer being less than the source of the continuous spectrum background, a broad line darker than the continuous spectrum is produced. In the case of the next layer, the so-called emitting layer, its pressure and temperature are both reduced in reference to the underlying layer. The decrease of pressure results in a narrower line, but its lower temperature does not necessarily imply a decreased radiation, as on nearing the center of the line the coefficient of radiation rapidly increases, and if the gain due to a higher coefficient of radiation exceeds the loss due to decrease of temperature the result would be a relatively narrow bright line superposed upon the center of the K_1 line. This result would be favored by the greater scattering of the light coming from the lowest layer, which would tend to darken the background by reducing the light in the K_1 line.

Spectroheliograms taken with the first slit on the K_1 line, at decreasing distances from the center of the line, and then with the slit on the K_2 line, in the opinion of solar observers, represent different levels in the solar atmosphere, rising in level as the slit approaches the center of the line. The area of a flocculus increases progressively, reaching its maximum area according to M. Deslandres, when photographed by the light from the K_3 line. These appearances have been interpreted as indicating a tree-like structure of the rising column of calcium vapor. A diagram illustrating this view is given by W. J. S. Lockyer in *Nature*, **69**, 611, 1904. This implies that the calcium vapor is rising over the faculae, an assumption which the wave-length measurements obtained in this investigation do not appear to justify.

An explanation of the effects obtained at different levels by employing the parts of the K line in taking monochromatic photographs is here based upon the selective absorption in different parts of the K line which determines the depths in the solar atmosphere from which light of the different parts of the line reaches us, and upon the great sensitiveness of the H and K lines to changes of temperature or excitation. The faculae may be considered as regions from which a disturbance is propagated into the overlying gaseous masses. These may be regions of higher surface-temperature, absolutely or from their being elevated above a portion of the surrounding vapors, or as Professor Newall suggests:

> Under the influence of local disturbances, regions of the Sun may emit corpuscles which succeed in penetrating the lower strata of the reversing layer, and cause higher strata to glow as if their effective temperature were higher than lower strata, and thus bright flocculi arise.[1]

In either of the above cases the disturbing influence would tend to spread radially from the center of disturbance and increase the radiation coefficient of the calcium vapor perhaps selectively even within the K line. Mr. King has shown in his work with the electric furnace that the intensity of the H and K lines is very susceptible to temperature changes without corresponding changes in the width. For a narrow range of wave-length, represented by the width of K_3, the radiation increment may be assumed to be large; through a range of wave-length corresponding to the difference between the widths of K_3 and K_2 the increment would be less; while for wave-lengths between the boundaries of K_2 and K_1 the increment would be extremely small. The diagram in Fig. 3 will illustrate the manner in which the area of a flocculus would vary for different parts of the H and K lines.

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[1] *Monthly Notices of the Royal Astronomical Society*, **69**, 343, 1909.

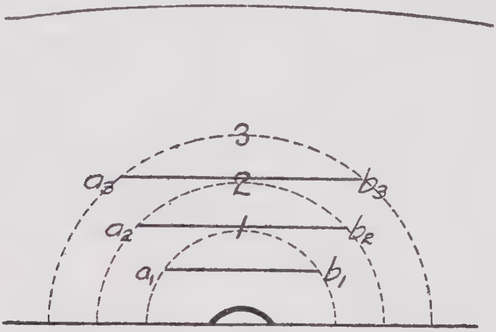

FIG. 3

The distance of the line $a_3\ b_3$ below the upper surface indicates the depth to which we see into the solar atmosphere by the light of the K_3 line; the half-circle marked 3 represents the limit of the appreciable effect upon the K_3 line produced by the disturbance propagated from the facula. As the first slit of the spectroheliograph, set upon the K_3 line, moves over the region an area much larger than the facula would be bright relatively to that photographed by the neighboring parts of the K_3 line. For wave-lengths differing slightly from K_3 the increase of radiation would not be so great for equal excitation, but the depth from which the light comes would be greater. The level therefore from which the light of the K_2 line comes, is lower owing to the decreased absorption. At this depth the excitation may be intense enough to be effective upon the radiation of this wave-length, thus increasing the intensity of K_2 in comparison with the intensity of the adjoining parts of the line. The area photographed by the K_2 line would be less than that photographed by the K_3 line, but still considerably larger than the facula as indicated in the diagram by the line a_2 b_2 and the corresponding circle.

In the case of the K_1 line the light comes from a still greater depth, but for wave-lengths differing so much from the center of the line the increased excitation is very much less effective in increasing radiation than in the case of K_2 and K_3, and the distances from the center of disturbance at which the excitation is sufficient to increase the radiation in K_1 over the facula in comparison to the radiation in the neighboring parts of the line are much less, and the areas photographed by setting the first slit of the spectroheliograph at increasing distances from K_3 would approach the area of the facula as a limit.

There is probably a piling up of calcium vapor over the penumbrae of spots and the surrounding faculae, evidenced both by the greatly increased width of the K_2 line over these regions and the absence of appreciable motion of ascent or descent of the emitting vapor as shown by the wave-length determinations, though it is rising rapidly over the general surface. It is difficult to believe that it is not rising through the faculae as elsewhere. The descent of the upper portions of the layer toward the umbrae of spots and the great thickness of the layer would tend to mask the rising vapor that is probably being added to the mass from below and perhaps crowding it slowly upward, the down-flow into the umbrae being supplied by the inflow from the surroundings of the flocculi. That there is an intimate connection between the faculae and the accompanying flocculi is indicated by their community of form and location. Such a nodal condition as is indicated by the normal wave-length of the K_2 line over the faculae surrounding spots might be favorable to an accumulation of calcium vapor as a kind of back-water effect where opposing currents tend to annul each other. The observations upon which this paper is founded were made upon completely developed spots. It would probably give added light to the subject to study the motions of calcium vapor over developing faculae and spots, and be particularly interesting to observe the initial conditions in the case of a large flocculus.

From the point of view of the combined action of absorption and scattering, Professor Schuster[1] has considered the radiation of a gaseous layer of uniform temperature and of a layer in which the temperature variation is such that the radiation of a black body varies directly with the distance from the front surface. In the latter case, the only one which approximates solar conditions, he shows that for certain values of the coefficients of absorption and scattering homogeneous radiations may appear bright with a dark center. Bright in this sense means brighter than the continuous spectrum, but the solar H_2 and K_2 lines are less bright than the continuous spectrum. Professor Schuster finds that for certain values of the coefficients the intensity of homogeneous radiations rises to a maximum which is greater than the intensity of the continuous spectrum, then falls for larger values of the coefficient of absorption which obtain as the center of the line is approached. The problem to be solved, however, is that in which the intensity-curve for the line has a minimum corresponding to K_1, a maximum corresponding to K_2, and a second minimum corresponding to K_3, all less than the continuous spectrum, and occurring with progressively increasing coefficients of absorption and progressively decreasing thicknesses of the effective layers. Its solution requires a knowledge of the coefficient of scattering, and of the radiation-gradient which probably differs greatly for the wave-lengths concerned in the production of the K_1, K_2, and K_3 lines; as Professor Schuster points out, the radiation-gradient depends not only on the temperature-gradient but also on the wave-length.

GENERAL CONCLUSIONS

1. In the great majority of sun-spots the calcium vapor is descending in the umbrae with velocities varying from 0.68 km per second to 2.2 km per second. This result is obtained from the usual bright reversal over the umbrae and also from the absorption

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[1] *Astrophysical Journal*, **21**, 1, 1905.

line when present. Occasionally the calcium vapor is rising in the umbrae.

2. Over the penumbrae of spots the calcium vapor which is the source of the bright line K_2 has little, if any, vertical motion. The calcium vapor producing the absorption line is descending with approximately the same mean velocity as over the general disk.

3. Over flocculi surrounding spots the emitting vapor shows a very slight but doubtful upward motion. The mean wave-length for K_2 over the central flocculi is 3933.665 Å compared with 3933.667 Å in the arc, an agreement within the errors of measurement. The absorbing vapor, the source of the K_3 line, is descending with the same mean velocity as over the general disk.

4. Over circumfloccular regions the upper layer of absorbing calcium vapor is descending with practically the same mean velocity as over the general disk, and does not show evidence of a local system of circulation involving the flocculi and their immediate surroundings.

5. A radial motion of the calcium vapor inward across the penumbrae is shown both by the emitting and absorbing vapor. The velocity is higher for the absorbing vapor than for the emitting vapor.

6. A rotary motion of the calcium vapor around the umbrae of spots is an occasional phenomenon, and is shown by the displacements of both the absorption line and the bright line. The velocity is higher in the case of the absorbing vapor than in the case of the emitting vapor.

7. The combination of the radial motion inward and the rotary motion results in a spiral or a vortical motion converging upon the umbra. The direction of rotation does not depend upon whether the spot is north or south of the sun's equator. The disturbance appears to originate in the high-level absorbing vapor and to work downward, involving the emitting layer.

8. The phenomenon of a dark absorption line appearing in one of the K_2 components, or beyond their outer edges, while the K_3 line is undisturbed, is interpreted as being caused by detached masses of relatively cool calcium vapor high above the chromo-

sphere, and in more or less rapid motion, that is, by prominences projected against the sun's disk.

9. In addition to the general circulation of the calcium vapor shown by the ascent of the emitting vapor and the descent of the absorping vapor over the general surface of the sun, there appears to be a local system in which the emitting vapor rises around the flocculi, flows across the penumbra, and is then drawn downward into the umbra with or without vortical motion. There is very slight evidence, if any, of its rising from the interior of the sun through the faculae, except in the case of eruptions.

10. The intensity of the bright K_2 line over flocculi is less than that of the continuous spectrum. The apparent weakness of the K_2 line in the spectrum of the center of the sun is due mainly to the slight difference between it and the background of the K_1 line. Its apparent increase of intensity at the limb is due in the main to the greater absorption in the K_1 and K_3 lines which raises the K_2 line into relief without much actual increase of intensity.

11. The relative intensities of the K_1, K_2, and K_3 lines may be explained by the great differences in their radiation coefficients and the consequent different depths in the solar atmosphere from which light of their respective wave-lengths reaches the surface owing to selective absorption. The occurrence of the bright emission line K_2 would be favored by the scattering of the light from the still lower layer.

12. The results for different levels obtained by the spectroheliograph find a possible explanation through considering the underlying faculae as sources of disturbance propagated into the overlying masses of calcium vapor and increasing in different degrees the radiation coefficients of the components of the K line.

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THE ZEEMAN EFFECT FOR VANADIUM

By HAROLD D. BABCOCK

On account of the importance of vanadium in the study of magnetic fields in sun-spots, the following material is presented now. It is preliminary to a fuller discussion of the subject which must be deferred for a period.

The apparatus employed and the manner of taking the photographs have been described in a preceding paper.[1] The field-strengths employed for different plates ranged from 17,500 to 19,800 gausses. For nearly all of the plates lumps of pure vanadium were used as spark terminals, but two photographs were taken with pieces of ferro-vanadium supposed to contain ten per cent of the metal. This substance in the spark yields the vanadium lines in abundance, as well as the stronger iron lines.

In Table I are given the results obtained from all the plates taken up to this time. From λ 5500 to λ 6600 the number of plates upon which the results depend is relatively greater than for the remainder of the spectrum. The wave-lengths employed are those of Hasselberg[2] and of Shaw,[3] except for a very few lines given only by Exner and Haschek.[4] The wave-lengths taken from Shaw's paper are on the Rowland system.

The second column of the table gives the total number of components into which the line appears separated when viewed at right angles to the magnetic field. The number 1, which is occasionally found in this column, indicates that the line is undivided by the field. The letter C, with or without a number, is used here as an abbreviation for complex, and signifies that higher resolving power is required for the complete analysis of the components. If a number accompanies the letter it indicates how many groups of components were observed. Measures given for such lines refer to the average separations of the groups of components unless otherwise noted in the remarks.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 52; *Astrophysical Journal*, **33**, 217, 1911.

[2] B. Hasselberg, "Die Spectra der Metalle im electrischen Flammenbogen," *Kongl. Svenska Vetenkaps-Akademiens Handlingar*, Bandet **32**, No. 2.

[3] H. Shaw, "The Arc Spectrum of Vanadium," *Astrophysical Journal*, **30**, 127, 1909.

[4] *Wellenlängen Tabellen der Funkenspectren der Elemente*, Leipzig and Vienna, 1902.

The third and fourth columns show the separations in Ångströms for the *n*- and *p*-components, respectively, for a field-strength of 20,000 gausses, while the fifth and sixth columns contain for the same field the corresponding values of $\Delta\lambda \cdot 10^8/\lambda^2$.

In some cases it was impossible to measure both members of a pair of components on account of blending with neighboring lines. For such the component clearly shown was referred to the normal position of the line, and the measured difference doubled.

In the "Remarks" column numbers are used to express the relative intensities of the components of a group in case they differ. The relative position of the numbers corresponds to that of the components when viewed with longer wave-lengths on the right. Thus *n* 2:1 means that of the two *n*-components of a line the one on the violet side is twice as intense as the other. No attempt is made to compare the intensities of *n*-components with those of *p*-components. In this column E means that the line is given in Lockyer's list of enhanced lines; –r means not resolved; w with a subscript means widened, the magnitude of the subscript indicating the amount of widening; w_3 represents the greatest widening observed.

As regards types of separation, vanadium is simpler than chromium. It has very few cases of asymmetry and comparatively few lines of more than four components. The largest number of components observed for one line is 12, for λ 6119.74. The one line having ten components is λ 6081.66. There are twenty lines having six components, two each of five, seven, and eight, and eight undivided lines. In addition to these there are 46 quadruple, 349 triple lines, and some whose classification is uncertain.

The average value of $\Delta\lambda \cdot 10^8/\lambda^2$ for all the triplets is 2.20, the extremes being 0.71 and 6.01. For those triplets which lie

TABLE I

Separation of Vanadium Lines in Magnetic Field

λ	Components	Δλ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
3865.02	3?	0.279	.....	1.87	....	*p* not observed
3867.00	3	0.392	.....	2.62	....	E
3867.77	3	0.357	.....	2.39	....	
3871.23	3	0.326	.....	2.18	....	
3873.80	1?	.....	.....	....	....	
3875.22	3	0.331	.....	2.20	....	
3876.05	6?	0.440	.....	2.93	....	*p*-components uncertain
3876.21	4	0.314	0.173	2.09	1.15	
3878.90	3	0.304	.....	2.02	....	E
3879.82	3	.....	.....	....	....	
3884.04	3	.....	.....	....	....	
3885.00	4	0.240	0.243	1.59	1.61	E
3886.72	3	0.178	.....	1.18	....	
3890.33	4	0.294	0.244	1.94	1.61	
3893.03	3	0.420	.....	2.77	....	
3896.29	1	.....	.....	....	......	
3897.22	3	0.310	.....	2.04	..	
3898.15	3	0.210	.....	1.38	....	
3899.30	3	0.282	.....	1.85	....	E
3900.33	3	.....	.....	....	......	Too weak to measure
3901.30	3	0.320	.....	2.10	....	*p*-component not sharp
3902.40	3	0.364	.....	2.39	....	
3903.42	3	0.381	.....	2.50	....	E
3906.89	3	0.412	.....	2.69	....	
3910.01	3 3	0.442 0.253	....	2.89 1.66	....	Double line –r
3910.95	4	0.315	0.116	2.06	0.76	
3912.36	4	0.301 0.000	....	1.97 0.00	....	N 1:2:1; 1 *p*-component
3913.03	3	0.379	.....	2.47	....	
3914.44	3	0.239	.....	1.56	....	E
3916.55	3	0.250	.....	1.63	....	E; *p*-component w_1
3920.15	3	0.408	.....	2.66	....	*n*-components of this line and the following blended and measured together
3920.65	4	0.408	0.161	2.66	1.05	
3922.05	6	0.484 0.186	0.160	3.15 1.21	1.04	
3922.58	3	0.376	.....	2.44	....	
3924.84	3	0.338	.....	2.19	....	
3930.19	3	0.295	.....	1.91	....	
3931.50	3	0.272	.....	1.76	....	
3934.16	3	0.398	.....	2.51	....	Measured normal and red component
3935.28	3	0.185	.....	1.20	....	
3936.42	3	0.579	.....	3.74	....	*p*-component w_3; very weak
3937.68	3	0.429	.....	2.77	....	
3938.35	3	0.292	.....	1.88	....	

TABLE I—*Continued*

λ	Components	Δλ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
3939.48	3	0.444	.....	2.86	....	*p*-component w_2 diffuse
3942.16	3	0.446	.....	2.87	....	*p*-component w_2 diffuse
3943.77	3	0.426	.....	2.74	....	
3950.37	3	0.281	.....	1.80	....	
3952.09	3	0.346	.....	2.22	....	E; fringed to red
3963.77	3	0.272	.....	1.73	....	Very difficult
3968.24	1	.....	.....	....	....	
3973.79	3	0.253	.....	1.60	....	E
3979.30	3	0.345	.....	2.18	....	
3979.59	3	0.272	.....	1.72	....	
3980.66	3	0.263	.....	1.66	....	
3984.75	4	.....	0.240	....	1.52	*n*-components too weak to measure
3985.90	3	0.296	.....	1.86	....	E
3988.97	4	.....	0.210	....	1.32	*n*-components too weak to measure
3990.71	3?	0.265	.....	1.66	....	
3992.95	3	0.307	.....	1.93	....	
3997.30	3	0.298	.....	1.86	....	E
3998.87	3	0.321	.....	2.01	....	
3999.30	3	0.296	.....	1.85	....	E
4003.10	6	0.438 0.074	0.367	2.73 0.46	2.29	
4005.86	3	0.361	.....	2.25	....	E
4017.00	3	0.276	.....	1.71	....	E
4023.50	3	0.310	.....	1.92	....	E
4031.37	4	0.395	.....	2.43	....	2 *p*-components too weak to measure
4031.98	3	0.330	.....	2.03	....	
4035.77	3	0.227	.....	1.39	....	E
4036.93	4	0.373	0.242	2.29	1.48	*n*-components; w_2 not sharp
4042.78	3	0.288	.....	1.76	....	*p*-component w_2
4048.77	3	0.341	.....	2.08	....	Red component wider than violet
4051.11	3	0.383	.....	2.33	....	Measured normal and violet component
4051.48	3	0.391	.....	2.38	....	Measured normal and red component
4053.80	3	0.302	.....	1.84	....	E; not sharp
4057.21	3	0.303	.....	1.84	....	
4064.09	3	0.202	.....	1.22	....	
4065.20	3	0.282	.....	1.71	....	E; *p*-component w_1
4067.90	3	0.366	.....	2.21	....	Difficult; *p*-component w_2
4071.67	3	0.318	.....	1.92	....	*p*-component w_1
4090.70	3	0.352	.....	2.10	....	
4092.09	4	0.270	0.283	1.61	1.69	*n* 1:2
4092.54	3	0.460	.....	2.75	....	Components shifted 0.048 Å to red; w_2
4092.83	3	0.445	.....	2.66	....	
4093.65	4	0.429	0.414	2.56	2.49	

TABLE I—*Continued*

λ	Components	$\Delta\lambda$ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
4094.42	3	0.374	.....	2.23	....	Difficult; components w_3
4095.64	3	0.331	.....	1.97	....	
4097.09	4?	.....	0.191	....	1.14	*n*-components not measurable
4098.54	4?	.....	0.396	....	2.36	*n*-components not measurable
4099.93	3	0.454	.....	2.70	....	
4102.32	3	0.275	.....	1.63	....	
4104.55	3	0.419	.....	2.49	....	
4104.92	3	0.435	.....	2.58	....	Measured normal and violet component
4105.32	3	0.466	.....	2.77	....	
4107.64	4?	.....	0.442	....	2.62	*n*-components not measurable
4108.36	3	0.236	.....	1.40	....	
4109.94	6	0.791 0.340	0.227	4.68 2.01	1.34	
4111.92	3	0.467	.....	2.76	....	
4112.47	3	0.344	.....	2.04	....	Measured normal and red component
4113.65	3	0.362	.....	2.14	....	w_1
4115.32	3	0.490	.....	2.89	....	
4116.64	5	1.026 0.511	....	6.20 3.02	....	See description in text
4118.34	3	0.362	.....	2.14	....	w_1; measured normal and violet component
4118.73	4	0.425	0.182	2.51	1.07	Diffuse; measured normal and red component
4119.58	4	0.396	0.242	2.33	1.43	Components w_2; not sharp
4120.69	6	0.365 0.149	0.334	2.15 0.88	1.97	Weak; not sharp
4123.65	6	0.810 0.345	0.245	4.76 2.03	1.44	Outer *n*-components lightly fringed outside
4124.23	4	0.354	0.182	2.08	1.07	
4128.25	3	0.475	.....	2.79	.....	
4129.00	3	0.149	.....	0.87	....	Not sharp
4132.13	3	0.470	.....	2.75		
4133.92	3	0.483	.....	2.83	....	
4134.61	3	0.471	.....	2.75	....	
4136.25	4	0.346	0.165	2.02	0.96	
4139.39	3	0.468	.....	2.73	....	
4149.02	3	0.358	.....	2.08	....	
4150.84	3	0.334	.....	1.94	....	
4159.84	1	.....	.....	....	....	w_3; not sharp
4171.45	4	0.419	0.152	2.41	0.87	
4174.18	3	0.384	.....	2.20	....	
4177.25	3	0.460	.....	2.64	....	Very difficult; w_2
4178.50	3	0.306	...	1.75	....	E; w_2; not sharp
4179.53	4	.....	0.529	....	3.03	*n*-components not measurable; *p*-components fringed inside

TABLE I—*Continued*

λ	Components	Δλ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
4182.23	3	0.310	.....	1.77	....	
4182.74	1	.....	.....	....	....	w_3; not sharp
4183.59	3	0.360	.....	2.06	....	E
4191.70	4	0.516 0.000	....	2.94 0.00	....	*n* 3:2:3; 1 *p*-component
4197.77	3	0.340	.....	1.93	....	
4202.52	3	0.395	.....	2.24	....	E; w_1
4204.67	4	0.524	.....	2.96	....	Weak, not sharp, w_2
4205.23	3	0.332	.....	1.88	....	E
4209.98	4	0.480	.....	2.71	....	*p*-components not measurable; w_3; not sharp
4224.30	3	0.501	.....	2.81	....	
4225.40	3	0.263	.....	1.47	....	E
4226.78	3	0.540	.....	3.02	....	Weak; measured normal and violet component
4227.90	3	0.334	.....	1.87	....	
4232.20	3	0.451	.....	2.52	....	E
4232.62	3	0.451	.....	2.52	....	
4233.09	3	0.415	.....	2.32	....	
4234.12	3	0.360	.....	2.01	....	
4234.70	4	0.328	0.185	1.83	1.03	Not sharp
4235.90	3	0.128	.....	0.71	....	
4243.10	3	0.326	.....	1.81	....	E; not sharp
4247.46	3	0.468	.....	2.60	....	*p*-component w_2
4254.55	3	0.435	.....	2.40	....	
4257.53	3	0.516	.....	2.85	....	
4259.46	3	0.416	.....	2.29	....	
4262.32	3	0.533	.....	2.94	....	
4265.28	3	0.395	.....	2.17	....	
4267.50	3	0.526	.....	2.89	....	
4268.78	3	0.414	.....	2.27	....	
4269.92	3?	0.670	.....	3.68	....	*p*-component w_3
4270.49	3	0.447	.....	2.45	....	
4271.71	3	0.384	.....	2.10	....	
4277.12	3	0.330	.....	1.80	....	
4284.19	3	0.238	.....	1.30	....	
4286.57	3	0.520	.....	2.83	....	Difficult
4287.97	3	0.385	.....	2.10	....	
4289.89	3	0.572	.....	3.11	....	*p*-component diffuse
4291.97	3	0.381	.....	2.07	....	
4296.28	3	0.354	.....	1.92	....	
4297.86	3	0.329	.....	1.78	....	
4298.17	3	0.298	.....	1.61	....	*p*-component w_2
4302.30	3	0.329	.....	1.78	....	
4305.63	3	0.411	.....	2.22	....	
4306.35	3	0.523	.....	2.82	....	
4307.33	3	0.521	.....	2.81	....	w_2; diffuse
4309.95	3	0.517	.....	2.78	....	
4330.18	3	0.143	.....	0.76	....	
4332.98	3	0.354	.....	1.88	....	
4341.15	3	0.430	.....	2.28	....	

TABLE I—*Continued*

λ	Components	$\Delta\lambda$ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
4343.00	3	0.325	.....	1.72	....	
4340.59	3	0.305	.....	1.61	....	*p*-component diffuse; difficult
4353.02	3	0.469	.....	2.48	....	
4355.09	3	0.393	.....	2.07	....	
4356.10	3	0.613	.....	3.23	....	*p*-component w_3
4363.69	3	0.560	.....	2.94	....	
4364.37	3	0.191	.....	1.00	....	
4368.25	3	0.560	.....	2.94	....	*p*-component w_1
4368.76	3	0.357	.....	1.87	....	
4373.40	3	0.398	.....	2.08	....	
4373.99	3	0.396	.....	2.07	....	
4375.47	3	0.386	.....	2.02	....	*n*-component w_2
4379.38	3	0.449	.....	2.34	....	Very strong, w_3
4380.69	3	0.457	.....	2.38	....	Measured normal and violet component
4384.87	3	0.429	.....	2.23	....	
4390.13	3	0.405	.....	2.10	....	Very strong, w_3
4392.24	3	0.636	.....	3.30	......	
4394.01	3	0.348	.....	1.80	....	w_2
4395.40	3C	0.396	.....	2.05	....	
4399.63	3	0.310	.....	1.60	....	Difficult; *p*-component w_2
4400.74	5	0.785 0.000	0.409	4.05 0.00	2.11	*n* 1:3:1
4403.86	3	0.453	.....	2.34	....	
4406.30	3	0.395	.....	2.04	....	*p*-component diffuse
4406.80	4?	0.537	.....	2.76	....	2 strong *p*-components –r
4407.85	4	0.573	0.228	3.09	1.17	w_2; not well resolved
4408.36	4	.....	0.329	....	1.69	*n*-components blended with near-by lines; very strong, w_2
4408.67	6	0.676 0.309	0.471	3.48 1.59	2.42	*n* 1:2:2:1; *n*-components shifted 0.09 Å to red; w_2
4412.30	3	1.050	.....	5.40	....	*p*-components w_3; not sharp
4416.63	6	1.110 0.223	0.439	5.69 1.14	2.25	*n* 2:1:1:2
4420.08	3	0.639	.....	3.27	....	
4421.73	3C	0.894	.....	4.57	....	
4423.32	3	0.408	.....	2.09	....	Probably double line; components blended; difficult
4423.41	3?	....	.....	....	....	See preceding line
4424.74	3	0.374	.....	1.91	....	Very weak
4425.86	1?	.....	.....	....	....	
4426.17	3	0.729	.....	3.72	....	*p*-component w_2
4428.68	3	0.677	.....	3.45	....	
4429.95	3	0.655	.....	3.34	....	*p*-component w_2; not sharp

TABLE I—*Continued*

λ	Components	$\Delta\lambda$ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
4430.68	3	0.900	.....	4.58	....	
4434.80	3	0.425	.....	2.16	....	Diffuse
4436.31	6	1.029 0.682	0.189	5.23 3.47	0.96	*n* 1:3:3:1
4438.02	3?	0.594	.....	3.02	....	*p*-component w_3
4441.88	4	0.641	0.206	3.25	1.04	w_1
4443.52	3	0.367	.....	1.86	....	Measured normal and red component
4444.40	4	0.768	0.282	3.89	1.43	w_1
4449.77	3	0.355	.....	1.79	....	
4451.09	3	0.367	.....	1.85	....	
4452.19	3	0.399	.....	2.01	....	
4457.65	8?	0.440 0.197	....	2.22 0.99	....	*p*-component w_3, sharp, probably four parts −r
4457.97	3	0.365	.....	1.84	....	Measured normal and red component
4459.93	3	0.374	.....	1.88		*p*-component w_2
4460.46	3	0.459	.....	2.31	....	w_2
4462.56	3	0.373	.....	1.87	....	
4468.19	3	0.524	.....	2.63	....	w_2, diffuse
4469.88	3	0.369	.....	1.85	....	
4474.21	3	0.427	.....	2.13	....	
4474.89	3	0.391	.....	1.95	....	
4480.20	4	0.405	0.240	2.02	1.20	Weak and diffuse
4489.06	3	0.375	.....	1.86	....	w_2
4490.95	3	0.476	.....	2.36	....	
4496.26	3	0.393	.....	1.94	....	
4502.12	3	0.425	.....	2.10	....	
4509.49	4?	.....	0.450	.....	2.21	*n*-components not measurable
4513.79	3	0.470	.....	2.31	......	
4514.36	3	0.336	.....	1.65	....	
4520.67	4?	.....	0.247	....	1.21	*n*-components not measurable
4524.38	3	0.440	.....	2.15	....	*p*-component w_2; slightly shifted to violet
4525.31	5	0.785 0.377	.....	3.84 1.84	....	*p*-component w_3, diffuse. Also *Fe* line
4528.16	3	0.458	.....	2.23	....	Measured normal and violet component
4528.66	3	0.460	.....	2.24	....	E
4529.47	3	0.392	.....	1.91	....	Difficult
4529.76	3	0.288	.....	1.40	....	
4530.97	3	0.436	.....	2.12	....	
4537.84	3	0.458	.....	2.22	....	
4540.18	3?	0.595	.....	2.89	....	w_2, diffuse
4545.57	3	0.425	.....	2.06	....	
4549.81	3	0.395	.....	1.91	....	
4552.05	3	0.409	.....	1.97	....	
4553.25	3	0.385	.....	1.86	....	
4560.90	3	0.399	.....	1.92	......	

TABLE I—*Continued*

λ	Components	$\Delta\lambda$ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
4564.76	3	0.378	.....	1.81	....	E, w_1
4570.60	4	0.465	0.252	2.23	1.21	
4571.96	3	0.366	.....	1.75	....	
4577.36	3	0.282	.....	1.35	....	
4578.92	3	0.307	.....	1.46	....	
4579.38	4	0.478	0.286	2.28	1.36	
4580.57	3	0.360	.....	1.72	....	
4583.96	4	0.461	0.383	2.19	1.82	Diffuse
4586.54	3	0.412	.....	1.96	....	
4590.70	3	0.470	.....	2.23	....	
4591.39	3	0.406	.....	1.93	....	
4594.27	3	0.442	.....	2.09	....	
4600.34	3	0.317	.....	1.50	....	E, diffuse
4606.33	4?	.....	0.425	....	2.00	*n*-components not measurable
4609.84	4	0.463	0.220	2.18	1.04	
4611.10	4?	.....	0.362	....	1.70	*n*-components not measurable
4619.85	3	0.392	.....	1.84	....	*n*-components of this line and the following blended and measured together
4619.97	4	0.392	0.267	1.84	1.25	
4624.62	4	0.583	0.346	2.73	1.62	w_2
4626.67	4	0.545	0.535	2.55	2.50	
4635.35	4	0.508	0.247	2.37	1.15	Diffuse
4640.25	4	0.144	0.311	0.67	1.44	
4640.92	4	0.635	0.181	2.95	0.84	
4644.64	3	0.540	.....	2.50	....	
4646.59	3	0.408	.....	1.89	....	
4670.66	3	0.487	.....	2.23	....	
4687.10	3	0.616	.....	2.80	....	*p*-component w_2
4699.52	3	0.463	.....	2.10	....	
4705.26	3	0.487	.....	2.20	....	
4706.34	3	0.553	.....	2.50	....	
4706.75	3	0.443	.....	2.00	....	
4707.62	3	0.443	.....	2.00	....	
4710.74	3	0.436	.....	1.96	....	
4714.28	3	0.400	.....	1.80	....	
4716.08	3	0.391	.....	1.76	....	
4717.85	3	0.345	.....	1.55	....	
4721.70	3	0.431	.....	1.93	....	
4723.06	3	0.494	.....	2.22	....	
4729.73	3	0.764	.....	3.41	....	
4730.57	3	0.436	.....	1.95	....	
4742.79	3	0.389	.....	1.73	....	
4746.81	4?	.....	0.684	....	3.04	*n*-components very diffuse
4748.70	4?	.....	0.427	....	1.89	*n*-components very diffuse
4751.16	4	0.549	0.361	2.43	1.60	Diffuse

TABLE I—*Continued*

λ	Components	Δλ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
4751.75	3	0.683	.....	3.02	....	Diffuse; measured normal and red component
4754.13	4	0.578	0.258	2.56	1.14	Diffuse
4757.68	1	.....	.....	....	....	
4766.80	3	0.296	.....	1.30	....	
4776.54	3	0.380	.....	1.67	....	Violet component blended with that of the following
4776.70	3	0.532	.....	2.33	....	
4786.70	3	0.454	.....	1.98	....	
4797.07	3	0.490	.....	2.13	....	
4807.70	3	0.512	.....	2.22	....	
4827.62	4	0.598	0.228	2.57	0.99	
4831.80	4	0.520	0.350	2.23	1.50	Components w_2
4832.59	7	.....	0.541	....	2.32	Probably 5 *n*-components –r
4851.65	3	0.224	.....	0.95	....	
4864.93	3	0.405	.....	1.71	....	
4875.66	3	0.486	.....	2.04	....	
4881.75	3	0.526	.....	2.21	....	
4900.84	3	0.486	.....	2.02	....	
4904.59	3	0.500	.....	2.08	....	
4925.83	3	0.741	.....	3.05	....	
4932.24	3	0.725	.....	2.98	....	
5002.54	3	0.450	.....	1.80	....	
5014.83	3	0.436	.....	1.74	....	
5064.32	3	0.489	.....	1.91	....	
5105.37	3	0.431	.....	1.65	....	
5128.71	3	0.597	.....	2.27	....	
5138.58	3	0.566	.....	2.14	....	
5139.74	3	0.427	.....	1.62	....	
5148.95	3	0.532	.....	2.01	....	
5159.56	3	0.393	.....	1.48	....	w_2; diffuse
5170.15	3	.....	0.512	....	1.92	1 *n*-component, 2 *p*-components
5177.03	3	0.530	.....	1.98	....	
5192.22	3	0.317	.....	1.18	....	
5193.18	3	0.735	.....	2.73	....	
5193.82	3	0.495	.....	1.84	....	Measured normal and red component
5195.01	3	0.664	.....	2.46	....	
5195.58	3	0.612	.....	2.27	....	
5216.80	3	0.780	.....	2.87	....	
5225.97	3	0.781	.....	2.86	....	
5233.91	3	0.763	.....	2.78	....	
5234.31	3	0.458	.....	1.67	....	
5241.06	3	0.552	.....	2.01	....	
5385.39	3	0.633	.....	2.18	....	
5402.17	3	0.524	.....	1.80	....	
5415.51	3	0.579	.....	1.98	....	

TABLE I—*Continued*

λ	Components	$\Delta\lambda$ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
5434.43	3	0.631	.....	2.14	....	
5487.48	3	0.712	.....	2.36	....	
5488.18	3	0.650	.....	2.16	....	
5490.22	3	0.570	.....	1.91	....	
5505.13	6	0.942 0.372	0.324	3.11 1.23	1.07	*n* 1:3:3:1; poor
5507.97	3	0.452	.....	1.49	....	
5511.41	3	0.942	.....	3.10	....	
5546.18	3	1.083	.....	3.52	....	Measured normal and violet component
5547.31	3	1.032	.....	3.35	....	
5559.00	6	0.977 0.368	0.258	3.16 1.19	0.83	*n* 1:3:3:1
5561.92	4	0.864	.....	2.79	....	*p*-components too weak to measure
5584.75	3	0.898	.....	2.88	....	
5585.00	3	0.696	....	2.23	....	
5586.26	3	0.642	.....	2.06	....	
5588.71	3	0.778	.....	2.49	....	
5592.67	3	0.901	.....	2.88	....	
5601.63	3	0.648	.....	2.06	....	
5605.20	6	1.086 0.347	0.349	3.46 1.10	1.11	*n* 1:3:3:1
5624.80	3	0.824	.....	2.60	....	
5625.16	3	0.692	.....	2.19	....	
5626.27	1	.....	.....	....	....	
5627.86	3	0.863	.....	2.72	....	
5635.76	3	0.532	.....	1.67	....	
5646.36	6	1.080 0.350	0.363	3.39 1.10	1.14	*n* 3:1:1:3
5657.11	3?	0.453	.....	1.42	....	Measured normal and violet component; doubtful
5657.67	3	0.926	.....	2.89	....	
5668.61	3	0.916	.....	2.85	....	
5671.10	3C	0.400	.....	1.24	....	Strong, w_3; fringed
5683.47	4	0.696	.....	2.16	....	*p*-components too weak to measure
5698.74	3	0.593	.....	1.83	....	Strong, w_2
5703.83	3	0.571	.....	1.75	....	
5707.26	3	0.347	.....	1.06	....	Strong, w_2
5709.25	3	0.582	.....	1.78	....	
5716.49	3	0.706	.....	2.16	....	
5725.90	3	0.656	.....	2.00	....	
5727.25	3	0.700	.....	2.13	....	
5727.90	7	0.973 0.523 0.000	0.687	2.97 1.60 0.00	2.09	
5733.34	3	0.574	.....	1.75	....	
5734.26	3	0.598	.....	1.82	....	
5737.28	4	0.766	0.478	2.33	1.45	w_3

TABLE I—*Continued*

λ	Components	$\Delta\lambda$ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
5743.67	4	0.820	0.496	2.48	1.50	w_2
5747.98	3	0.684	.....	2.07	....	
5749.13	3	0.556	.....	1.68	....	
5750.90	3	0.839	.....	2.54	....	
5752.99	6	1.229 0.320	0.412	3.71 0.97	1.24	*n* 1:3:3:1
5761.70	6	1.810	0.820 0.264	5.45	2.47 0.80	
5772.66	3	0.724	.....	2.17	....	*n*-components lightly fringed outside
5776.95	4	0.576	0.779	1.72	2.33	
5783.76	3	0.477	.....	1.42	....	
5784.64	3	0.718	.....	2.14	....	
5786.42	3	0.630	.....	1.88	....	
5788.85	4	0.896	0.842	2.67	2.51	
5807.40	3	0.541	.....	1.60	....	w_2
5817.33	4	0.487	0.500	1.44	1.48	
5830.97	3	0.732	.....	2.15	....	Strong, w_2, not sharp
5846.56	3	0.796	.....	2.33	....	Not sharp, w_2
5850.60	4	0.976	0.356	2.85	1.04	
5924.80	3	0.775	.....	2.21	....	
5979.18	3	0.688	.....	1.92	....	
5981.03	3	0.682	.....	1.91	....	w_2
6002.60	3	0.782	.....	2.17	....	
6002.83	3	1.370	.....	3.80	....	
6008.97	4	0.839	0.955	2.32	2.65	
6016.38	3	0.698	.....	1.93	....	
6018.16	4?	.....	0.506	....	1.40	*n*-components not measurable
6022.02	3	0.708	.....	1.95	....	
6025.66	3	0.626	.....	1.72	....	
6039.95	4	0.992	0.341	2.72	0.93	
6054.78	3	0.615	.....	1.68	....	
6058.36	6	1.762 0.585	0.577	4.80 1.59	1.57	*n* 1:3:3:1
6063.56	3	0.521	.....	1.42	....	
6067.48	3	0.646	.....	1.76	....	
6081.66	10	1.372 1.007 0.621	0.552	3.71 2.72 1.68	1.49	*n* 2:3:2:2:3:2; inner *p*-components too weak to measure
6090.43	3C	0.857	.....	2.31	....	
6107.20	3	0.707	.....	1.90	....	
6111.85	4	0.878	0.895	2.35	2.40	
6119.74	12	0.719	0.388 0.135	1.92	1.04 0.36	*n* 1:2:3:4:4:3:2:1
6128.56	5	1.498 0.000	0.617	3.99 0.00	1.64	
6135.56	6	1.325 0.359	0.500	3.52 0.95	1.33	*n* 1:3:3:1

TABLE I—*Continued*

λ	Components	$\Delta\lambda$ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	*p*	*n*	*p*	
6150.35	3	0.846	.....	2.24	....	
6170.54	3	0.808	.....	2.12	....	
6189.57	3	0.719	.....	1.88	....	W_2
6190.67	4?	.....	0.840	....	2.19	*n*-components not measurable; *p*-components fringed inside
6199.38	3	1.054	.....	2.74	....	
6214.06	4	1.078	0.329	2.79	0.85	
6216.55	3	1.057	.....	2.74	....	
6218.55	3	0.959	.....	2.48	....	
6221.54	4?	.....	0.390	....	1.01	*n*-components uncertain
6224.71	4	1.072	0.393	2.77	1.01	
6230.98	3	1.018	.....	2.62	....	*n*-components fringed outside
6233.39	4	1.048	0.502	2.70	1.29	
6236.52	3	0.744	.....	1.91	....	
6240.35	8	1.545 1.092 0.618	0.762	3.97 2.80 1.59	1.96	
6243.02	4	1.314	0.557	3.37	1.43	
6243.29	3	1.151	....	2.95	....	
6245.43	4	1.076	1.421	2.76	3.64	
6252.02	3	1.133	.....	2.90	....	
6257.12	3	1.188	.....	3.03	....	
6258.79	3	2.354	.....	6.01	....	
6261.42	6	2.310 0.571	0.820	5.89 1.46	2.09	*n* 3:2:2:3
6266.54	3C	1.688	.....	4.30	....	
6269.05	3	1.406	.....	3.58	....	
6274.85	6	1.821 0.925	0.457	4.62 2.35	1.16	*n* 1:3:3:1
6282.57	3	0.858	.....	2.17	....	
6285.38	3	1.156	.....	2.93	....	
6293.03	3	1.114	.....	2.81	....	
6296.70	3	1.131	.....	2.85	....	
6309.98	3	1.004	.....	2.52	....	
6311.74	3	0.790	.....	1.98	....	
6321.47	3	1.152	.....	2.88	....	W_2
6324.93	3	0.828	.....	2.07	....	W_2
6327.05	3	0.834	.....	2.08	....	
6339.32	3	0.781	.....	1.94	....	
6349.68	3	0.701	.....	1.74	....	
6355.83	3	0.673	.....	1.66	....	
6357.53	3	0.589	.....	1.45	....	
6359.05	3	0.833	.....	2.06	....	
6361.51	3	0.788	.....	1.95	....	
6374.74	3	0.487	.....	1.20	....	
6379.58	3	0.734	.....	1.80	....	
6393.56	3	0.598	.....	1.46	....	
6430.75	3	0.990	.....	2.39	....	
6431.90	3	0.958	.....	2.32	....	

TABLE I—*Continued*

λ	Components	$\Delta\lambda$ for 20,000 Gausses		$\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$ for 20,000 Gausses		Remarks
		n	p	n	p	
6433.44	3	0.808	.....	1.95	....	
6438.35	3	0.863	.....	2.08	....	
6452.56	3	1.153	.....	2.77	....	
6488.33	3	0.877	.....	2.08	....	
6504.40	6	1.746 1.040	0.418	4.14 2.46	0.99	n 1:3:3:1
6531.66	3	1.262	.....	2.96	....	
6550.33	3	0.876	.....	2.04	....	
6558.28	3	0.920	.....	2.14	....	
6566.13	3	2.125	.....	4.93	....	
6606.20	6	..... 1.104	0.398	.... 2.53	0.91	Outer n-components too weak to measure
6625.05	3	1.125	.....	2.56	....	

between λ 3850 and λ 4800 the average is 2.17, which is the same as the corresponding quantity for chromium.[1] As in the case of the latter metal, so for vanadium, the values of $\Delta\lambda\cdot 10^8/\lambda^2$ for the triple lines occur in two main groups, of which one is much larger than the other. The first column of Table II shows a series of intervals in the values of $\Delta\lambda\cdot 10^8/\lambda^2$, while the second and third columns contain the numbers of values occurring in the intervals. The enhanced lines are given here separately in order to show that their grouping is not peculiar.

The average of all the values lying between 1.40 and 2.50 is 1.99 ± 0.011, while the average for the second group, between the limits 2.50 and 3.20, is 2.78 ± 0.012, the appended quantities being probable errors. For the enhanced lines the average is 1.95. Although the mean for the enhanced lines should be compared with the mean of those not enhanced, rather than with the general average, it does not appear that the enhanced lines are distinctly different from the others in their magnetic separation. The same conclusion was reached in the case of chromium.

For 46 quadruple lines the average value of $\Delta\lambda\cdot 10^8/\lambda^2$ for the n-components is 2.38, for the p-components 1.45.

There are a few peculiar lines in Table I to which attention should be called. The first is λ 4116.64, which has four n-components and only one *p*-component. The outer *n*-components show a very large separation and are shifted (by a field of 20,000 gausses) 0.033 Å to the red, while the inner pair are shifted 0.041 Å to the violet, the mean position of all four coinciding with the normal. $\lambda\lambda$ 3912.36 and 4191.70 each have three *n*-components and only one *p*-component. λ 5170.15 shows only one *n*-component, but two *p*-components—if other components exist they are very weak. λ 5761.70 is an interesting sextuple line having two widely separated *n*-components and four *p*-components. λ 5776.95 is a quadruple line of which the *p*-components are more widely separated than the *n*-components, in the ratio 4:3, while λ 4640.25 of the same type has its *p*-components twice as far apart as its *n*-components.

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[1] *Op. cit.*

TABLE II

DISTRIBUTION OF TRIPLET SEPARATIONS

INTERVALS IN $\frac{\Delta\lambda}{\lambda^2}\cdot 10^8$	NUMBER OF VALUES	
	Not Enhanced	Enhanced
0.60–0.80	2	..
0.80–1.00	2	..
1.00–1.20	4	..
1.20–1.40	7	1
1.40–1.60	11	3
1.60–1.80	37	5
1.80–2.00	59	9
2.00–2.20	67	2
2.20–2.40	38	4
2.40–2.60	17	2
2.60–2.80	27	1
2.80–3.00	28	..
3.00–3.20	6	..
3.20–3.40	5	..
3.40–3.60	4	..
3.60–3.80	2	..
3.80–6.20	5	..

For lines having more than three components various ratios of separation occur. These are collected in Table III. Ciphers in this table indicate central components coinciding with the normal position of the line.

The order of the ratios in any column corresponds to the frequency with which they occur, the most common ratio being at the top.

TABLE III

RATIOS OF SEPARATION

Total Number of Components						
4	5	6	7	8	10	12
2:1	0:2:5	1:1:3	0:3:4:6	4:5:7:10	?:1:1:2:3	1:3:6:?:?:?
3:1	0:1:2	2:3:8				
1:1		2:3:7				
5:3		1:3:7				
3:2		1:2:2				
3:4		1:2:4				
1:2		1:2:5				
		1:4:6				
		1:5:6				
		2:3:4				
		2:5:8				

My thanks are due to Mr. King for supplying two of the photographs used in this work, and to Miss Griffin for assistance in the reduction of the values.

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THE INFLUENCE OF A MAGNETIC FIELD UPON THE SPARK SPECTRA OF IRON AND TITANIUM—SUMMARY OF RESULTS

By ARTHUR S. KING

The purpose of this paper is to give an outline of a detailed study of the Zeeman effect for iron and titanium carried out in the Pasadena Laboratory of the Solar Observatory, which is being published in full under the above title by the Carnegie Institution of Washington in Vol. II of the *Papers of the Mount Wilson Solar Observatory*.

The range of wave-length covered is from λ 3660 to about λ 6700, slightly beyond this for titanium. Between these limits, 662 lines in the spark spectrum of iron and 458 in that of titanium have been treated, at least to the extent of describing their type of separation by the magnetic field.

The spectra of both iron and titanium have been investigated previously to some extent. Measurements for portions of the iron spectrum have been published by H. M. Reese,[1] N. A. Kent,[2] W. Hartmann,[3] and Mme. H. B. van Bilderbeek-van Meurs.[4] These measurements are confined for the most part to the blue and violet regions and cover only the stronger lines. For titanium, extensive lists have been published by J. E. Purvis[5] and by the author.[6] The former list is mainly for the ultra-violet, including the stronger lines. The present investigation includes about 50 per cent more lines than the previous one by me, the data being compiled from a much more extensive set of plates, taken with higher dispersion and stronger field. The gain in all points is so great that these measures may be taken as superseding the former list.

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[1] "An Investigation of the Zeeman Effect," *Astrophysical Journal*, **12**, 120, 1900.

[2] "Notes on the Zeeman Effect," *Astrophysical Journal*, **13**, 288, 1901.

[3] "Das Zeeman Phaenomen im sichtbaren Spectrum von Kupfer, Eisen, Gold, und Chrom," Dissertation, Halle, 1907.

[4] "Magnetische Splitsing van het Ultraviolette IJzerspectrum," Dissertation Amsterdam, 1909.

[5] "The Influence of a Strong Magnetic Field on the Spark Spectra of Titanium, Chromium, and Manganese," *Proceedings Cambridge Philosophical Society*, **14** (1), 41, 1906.

[6] "The Zeeman Effect for Titanium," *Contributions from the Mount Wilson Solar Observatory*, No. 39; *Astrophysical Journal*, **30**, 1, 1909.

The weaker lines in the two spectra have been photographed as far as they were obtainable, an object which has added to the labor and altered to some extent the experimental methods which would be used for the stronger lines alone. The tables for titanium contain all but the weakest of those lines given in the regular lists of arc and spark lines. As much cannot be claimed for iron, however, as numerous lines, fairly strong in the arc, are not brought out by the spark in the magnetic field even with an exposure of many hours. This is especially true of those lines of diffuse appearance, which are particularly numerous in the iron spectrum.

The publication summarizes the theory and the results of former investigations on the Zeeman effect so far as they apply directly to the present research. The apparatus and experimental methods are described in detail. The spark was given by a 5 K.W. transformer, the terminals being held between the poles of a Du Bois electro-magnet. The light was usually taken at right angles to the lines of magnetic force and passed through a Nicol prism placed above the slit of the vertical Littrow spectrograph. By rotating the Nicol through 90°, the components given by light vibrating parallel to the lines of force and in a plane perpendicular to the force-lines were successively photographed. A variety of field-strengths were used, sometimes slightly over 20,000 gausses, but all values for the tables were reduced to standard fields of 16,000 gausses for the iron spectrum and 17,500 gausses for that of titanium. A system of checking the field-strengths for different plates, somewhat difficult in the case of iron, was carried out, so that considerable confidence can be placed in the uniformity of the field for all parts of the spectrum.

The Littrow spectrograph was used with objectives of either 13 ft. (4 m) or 30 ft. (9.1 m) focal length, the third order of the plane grating generally being used at the shorter focus and the second order at the longer. Scales of about 1.3 and 0.95 Ångström units per mm, respectively, were obtained for photographs with the two arrangements, but dispersions as high as 0.62 and 0.44 Å per mm were occasionally employed with higher orders of the grating.

The photographic processes were adapted as nearly as possible to the somewhat conflicting requirements of speed, moderately fine grain, contrast sufficient to give sharply defined lines and still not such as to give too large differences in intensity between the stronger and weaker lines. For the most part, the Seed "27" plate was used for the blue end of the spectrum, and for wave-lengths greater than 4600 the same plate was sensitized by a three-dye bath. Regions of the spectrum containing a wide range in the intensity of lines often required special treatment both as to instrumental and photographic methods.

In the measurement of the plates, I am indebted to Miss Wickham and to Miss Griffin for much assistance.

In making extracts from the tables, there is no criterion which makes a certain class or type of lines of special importance for a summary of this sort, so the method adopted is to take the descriptions of lines for various short stretches of wave-length bodily from the complete tables. These regions are selected to represent as well as possible the types of separation occurring throughout the two spectra. Each region contains a number of strong lines and includes some complex types of separation. The change in average separation with the wave-length may be noted by comparing the general magnitude of the measurements in successive regions.

EXPLANATION OF THE TABLES

The letters *n* and *p* in the tables are used to denote the Zeeman components given by light vibrations in a plane at right angles to the lines of magnetic force and parallel to these respectively. The wave-lengths are on the Rowland system. The second column gives a rough value for the intensity of lines in the spark spectrum, taken partly from the tables of Exner and Haschek and partly estimated on the same scale from my plates. Weak lines are graded 1, but there is a considerable variation in the strength of lines which are given this value.

The third column gives the best judgment of the type of separation that can be made from the photographs. The description given must be considered in connection with the measured separation and widening of components given in the columns for $\Delta\lambda$ of the n- and p-components, and is usually made clear by these. Frequently a supplementary remark is needed in the case of complex lines. The interrogation point is freely used to indicate that the line is probably of the character given, though not clearly shown to be so on the plates. The reason for doubt is usually given in the columns for $\Delta\lambda$. Thus "triple?" means that the p-component is slightly widened and may not be simple, though the widening may be explained by the strength of the component or by the fact that the no-field line is slightly diffuse. "Quadruple?" signifies that the two n-components are fairly sharp, but the p-component is probably double. The doubtful sextuplet is very common and as a rule has its two n-components each widened so that there are probably two pairs, while the p-component is either distinctly double or unresolved and considerably widened. The questioned septuplet has almost the same appearance, but shows a central maximum to the widened p-component, indicating three constituents. Lines whose n-components shade off either outward or toward the center are given in the "Remarks" column as "fringed." The fringes indicate very close, unresolved components. If the structure of the line is very complex, an interrogation point is used without any attempt to give the number of components.

Although the character of separation is thus doubtful in many cases, the large number of plates from which the material was taken gave an opportunity to study each line under various conditions of intensity and degree of separation so that the classification as to character is probably as accurate as can be made without very much higher field-strength combined with as large dispersion as was here used.

In the fourth column, lines are weighted 3, 2, or 1 according as the quality of the components for measurement is good, fair, or poor. Weight 3 indicates that the components are sharply defined, the probable error of measurement being in the third decimal place, often not greater than two or three thousandths of an Ångström. Weight 2 is given to lines which do not permit such close measurement, but which as a rule have a probable error not greater than 10 per cent. Lines weighted 1 are either very faint, much disturbed by blends, or of such complex structure that the components are very diffuse. The error of measurement for such lines may be large, but the figures given show whether the line is to be classed as having small, medium, or large separation. When both the *n*- and the *p*-components are measurable, the weight for each is given, separated by a comma. In case only the *p*-component is measured, a dash before the comma indicates the omission of the weight for the *n*-component.

The fifth and sixth columns give the separation in Ångström units of the *n*- and *p*-components respectively. A single value denotes a pair of components. When there is more than one pair for the same polarization, the largest separation is given first, but the innermost pair is designated as "Pair I." When an odd number of *n*- or *p*-components is present, any outer components that may appear are measured from the central component, the latter being denoted by 0.000. The relative intensities of multiple components are indicated by figures in parentheses after the value of the separation.

The widening of individual components, which often denotes a blend of two or more, is indicated by "w" with subscript 1, 2, or 3, according to the degree of widening. The letter "w" in the *p*-component column shows that the unresolved component may not be single. If a measurement followed by "w" is given in the *n*-component column, a more or less diffuse pair is present, which might be resolved by higher field into two or more pairs.

The letters "n.m." indicate that a separation exists but is not measurable, generally by reason of faintness. In such cases it is usually possible to tell the character of the separation with fair certainty and the line is included on this account. When the components are hazy as well as faint "n.m.w." is used.

The seventh and eighth columns give the values of $\Delta\lambda/\lambda^2$, the positions in the column corresponding to those of the values of $\Delta\lambda$. When λ is expressed in Ångström units, the values given for $\Delta\lambda/\lambda^2$ are to be multiplied by 10^{-8}.

TABLE I

MEASUREMENTS OF ZEEMAN EFFECT FOR IRON

λ	INTENSITY	CHARACTER OF SEPARATION	WEIGHT	Δλ		Δλ/λ²		REMARKS
				n-Components	*p*-Components	*n*-Comp.	*p*-Comp.	
3722.071......	1	Triple	1	0.266	.....	1.920	.....	Faint in spark
3722.729......	4	12 comps.	2, 2	Pair IV, 0.415 (2)	Pair II, 0.195 (5)	2.994	1.407	
				Pair III, 0.311 (3)	Pair I, n.m. (1)	2.244	?	
				Pair II, 0.211 (3)	.....	1.522	.....	
				Pair I, 0.103 (2)	.....	0.743	.....	
3724.526......	2	Triple	3	0.256	.....	1.845	.....	
3727.778......	5	Septuple?	2	0.318 W_1	W_2	2.288	.....	*n*-comps. have inner fringes. Probably 3 *p*-comps.
3730.534......	1	Triple?	1	0.341 W_1	W_1	2.451	.....	Blend with faint lines
3731.093......	1	Triple	1	0.176	.....	1.264	.....	
3732.545......	2	Triple	3	0.399	.....	2.865	.....	
3733.469......	3	Quintuple	3, 3	0.157 (2)	0.322	1.127	2.311	
				0.000 (3)	.....	0.000	.....	
				0.158 (2)	.....	1.134	.....	
3735.014......	10	Triple	2	0.310	.....	2.222	.....	
3735.485......	1	Quadruple?	2, 2	0.472 W_1	0.166	3.384	1.190	
3737.281......	7	Septuple?	2	0.254 W_1	W_2	1.818	.....	*n*-comps. fringed. Probably 3 *p*-comps.
3738.454......	2	Triple	3	0.207	.....	1.481	.....	
3743.508......	6	Octuple	3, 3	0.208 (4)	0.107 (2)	1.484	0.763	Comps. of faint line to red (computed 3743.615) are superposed on central and outer red *n*-comps., giving apparent dissymmetry. Compare 3788.046
				0.104 (2)	0.000 (3)	0.742	0.000	
				0.000 (2)	0.106 (2)	0.000	0.756	
				0.112 (2)		0.799	.....	
				0.213 (5)	.....	1.520	.....	
3744.251......	1	Septuple?	1, 1	0.401 W_2	0.283 (1)	2.861	2.018	Probably 4 *n*-comps. Apparently 3 *p*-comps., but faint. Compare 3747
					0.000 (1)	.....	0.000	
					0.415 (1)	.....	2.960	

3745.717......	5	Septuple?	2	0.228 W_1	W_2	1.624	....	*n*-comps. fringed. Probably 3 *p*-comps.
3746.058......	4	Unaffected	..	.....	.....	.....	.....	
3747.065......	1	Septuple?	1, 1	0.413 W_2	0.306 (1)	2.941	2.180	Apparently same type as 3744. Comps. more distinct
					0.000 (2)	.....	0.000	
					0.341 (1)	.....	2.429	
3748.408......	4	9 comps.?	2	Pair III, 0.316 (4)	W_3	2.250	.....	Probably 3 *p*-comps. almost resolved
				Pair II, 0.226 (3)	.....	1.609	.....	
				Pair I, 0.101 (1)	.....	0.719	.....	
3749.049......	1	Quadruple?	2	0.240 W_1	W_2	1.708	.....	
3749.631......	10	Triple	2	0.289	.....	2.055	.....	
3753.732......	2	Triple	3	0.395	.....	2.803	.....	
3756.213......	1	Triple?	2	0.300	W_1	2.126	.....	
3757.081......	1	Triple?	1	0.197	W_1	1.396	.....	
3757.597......	1	Triple	1	0.388	.....	2.747	.....	Faint in spark
3758.375......	8	Triple	3	0.269	.....	1.905	....	
3760.196......	2	Triple	3	0.235	.....	1.662	.....	
3760.679......	1	Quintuple?	3	0.146 (1)	W_2	1.032	.....	*n*-comp. appears as unsymmetrical triplet. No evidence of blend
				0.000 (1)	.....	0.000	.....	
				0.179 (1)	.....	1.265	.....	
3763.945......	6	Triple	3	0.218	.....	1.538	.....	
3765.689......	3	Triple	3	0.228	.....	1.608	.....	
3767.341......	5	Unaffected	..	.....	.....	.....	.....	
3768.173......	1	Triple	2	0.600	.....	4.225	.....	Faint in spark
3770.446......	1	Triple	2	0.191	.....	1.343	.....	
3773.803......	1	Unaffected	..	.....	.....	.....	.....	
3774.971......	1	Sextuple	2, 1	Pair II, 0.545 (1)	0.240	3.824	1.684	*p*-comps. faint
				Pair I, 0.274 (1)	.....	1.922	.....	
3776.600......	1	Triple?	2	0.229	W_1	1.605	.....	
3777.593......	1	Quadruple?	..	n.m.	n.m.	.....	.....	Very faint. Wide separation of *p*-comp.
3778.652......	1	Triple	1	0.344	.....	2.408	.....	
3779.569......	1	Triple?	1	0.277	.....	1.938	.....	
3781.330......	1	?	..	n.m.	W_2	.....	.....	Many comps. *n*-comps. diffuse. Not resolved
3786.092......	2	Triple	3	0.220	.....	1.535	.....	

TABLE I—*Continued*

λ	Intensity	Character of Separation	Weight	$\Delta\lambda$		$\Delta\lambda/\lambda^2$		Remarks
				n-Components	*p*-Components	*n*-Comp.	*p*-Comp.	
3786.314......	2	Triple ?	..	n.m.w_2	w_2	.....	.....	*n*-comps. diffuse
3786.820.....	2	Unaffected	..	.....	.....	.....	.....	
3788.046......	4	Octuple	3, 3	0.214 (4)	0.111 (2)	1.491	0.744	Magnetic duplicate of 3743.508
				0.108 (2)	0.000 (3)	0.753	0.000	
				0.000 (1)	0.109 (2)	0.000	0.760	
				0.111 (2)	.....	0.774	.....	
				0.219 (4)	.....	1.526	.....	
4233.772......	2	9 comps.	2, 2	Pair III, 0.780 (1)	0.140 (2)	4.351	0.780	
				Pair II, 0.550 (2)	0.000 (3)	3.068	0.000	
				Pair I, 0.265 (5)	0.140 (2)	1.478	0.780	
4236.112......	4	Triple	3	0.452	.....	2.519	.....	
4238.970......	1	Triple	2	0.320	.....	1.781	.....	
4240.014......	1	Triple	2	0.440	.....	2.447	.....	
4245.422......	1	Triple	3	0.493	.....	2.736	.....	
4246.251......	1	Triple	1	0.273	.....	1.514	.....	
4247.591......	1	Triple	3	0.356	.....	1.973	.....	
4248.384......	1	Triple	2	0.377	.....	2.089	.....	
4250.287......	8	Septuple ?	2	0.382 w_1	w_3	2.115	.....	*n*-comps. fringed. Probably 3 *p*-comps.
4250.945......	9	12 comps. ?	2, 2	0.246 w_3	0.211 w_1	1.361	1.168	Probably 8 *n*-, 4 *p*-comps.
4260.640......	10	Triple	3	0.423	.....	2.330	.....	
4267.122......	1	Triple	1	0.300	.....	1.648	.....	
4267.985......	1	Triple	1	0.528	.....	2.899	.....	
4268.915......	1	Triple ?	1	0.462	w_1	2.535	.....	
4271.325......	9	Triple	3	0.394	.....	2.160	.....	
4271.934......	10	Triple	3	0.341	.....	1.868	.....	
4282.565......	1	Septuple ?	2	0.310 w_2	w_3	1.691	.....	*n*-comps. fringed. Probably 3 *p*-comps.
4285.605......	1	Triple	3	0.315	.....	1.715	.....	
4294.301......	5	Sextuple ?	2, 2	0.319 w_2	0.138	1.730	0.748	*n*-comps. almost resolved

4298.195......	1	Triple ?	2	0.457	W₁	2.474	.....	
4299.410......	5	Triple	3	0.406	.....	2 197	.....	
4302.353......	1	Triple	2	0.316	.....	1.707	.....	Enhanced line
4303.337......	1	Sextuple ?	2, 2	0.415 W₂	0.265	2.241	1.431	Enhanced line
4305.614......	1	Quadruple ?	1	0.328 W₁	W₂	1.769	.....	
4308.081......	15	Triple	3	0.320	.....	1.724	.....	
4309.541......	1	Triple	2	0.325	.....	1.750	.....	
4315.262......	3	Sextuple ?	3, 3	0.517 W₁	0.090	2.777	0.483	
4325.939......	15	Triple	3	0.245	.....	1.309	.....	
4327.274......	1	Triple	2	0.313	.....	1.672	.....	
4328.080......	1	Triple	2	0.246	.....	1.313	.....	
4337.216......	2	Sextuple ?	2, 3	0.264 W₂	0.154	1.404	0.819	
4346.725......	1	Triple	1	0.292	W₂ ?	1.545	.....	Blend with air lines
4351.930......	1	Septuple ?	1	0.311 W₂	W₃	1.642	.....	Probably 3 *p*-comps. May be *Cr*, but given by Lockyer as enhanced line *Fe*
4352.908......	2	Septuple ?	2, 3	0.416 W₂	0.075 (1) 0.000 (2) 0.075 (1)	2.195	0.396 0.000 0.396	*n*-comps. fringed
4367.749......	1	Triple	2	0.311	.....	1.630	.....	
4369.941......	2	Triple	3	0.282	.....	1.477	.....	
4376.107......	2	Triple	3	0.424	.....	2.214	.....	
4383.720......	20	Triple	3	0.332	.....	1.727	.....	
4385.548......	1	Quadruple	2, 2	0.367	0.391	1.910	2.032	Enhanced line
4388.057......	1	Triple	..	n.m.	.....	.....	.....	*n*-comps. blended with adjacent lines
4388.571......	1	Triple	2	0.432	.....	2.243	.....	
4391.123......	1	Triple	..	n.m.	.....	.....	.....	Faint
4404.927......	15	Triple	3	0.334	.....	1.720	.....	
4407.871......	1	Triple ?	2	0.631	W₁	3.247	.....	
4408.582......	1	Triple ?	2	0.488	W₁	2.511	.....	
4415.293......	10	Septuple ?	2	0.338 W₂	W₂	1.734	.....	
4422.741......	1	Sextuple	2, 3	Pair II, 0.432 (1) Pair I, 0.154 (1)	0.280	2.208 0.787	1.431	*n*-comps. have inner fringes. Probably 3 *p*-comps.

TABLE I—*Continued*

λ	INTENSITY	CHARACTER OF SEPARATION	WEIGHT	Δλ		Δλ/λ²		REMARKS
				n-Components	*p*-Components	*n*-Comp.	*p*-Comp.	
5283.802......	3	Triple	3	0.623	.....	2.232	.....	
5302.480......	2	Triple	3	0.632	.....	2.272	.....	
5316.790......	4	Triple?	2	0.455 W_1	W_2	1.610	.....	Enhanced line. Diffuse comps. may be due to character of line
5324.373......	5	Triple	3	0.648	.....	2.286	.....	Red comp. slightly stronger than violet
5328.236......	7	Septuple?	2	0.470 W_1	W_3	1.656	.....	*n*-comps. fringed. Probably 3 *p*-comps.
5328.696......	3	Sextuple?	2, 2	0.488 W_2	0.275	1.718	0.968	
5340.121......	2	Triple	2	0.664	.....	2.329	.....	
5341.213......	3	?	1, 2	0.486 W_3	0.429	1.703	1.502	*n*-comps. blurred, probably at least 6
5353.571......	1	Triple	..	n.m.	.....	.....	.....	Very faint
5365.069......	1	Sextuple?	1	0.354 W_2	W_2	1.229	.....	Comps. very diffuse
5365.596......	1	Triple	1	0.471	.....	1.636	.....	Blend with preceding line
5367.669......	1	Triple?	2	0.414	W_1	1.437	.....	Diffuse
5370.166......	2	Triple?	2	0.456	W_1	1.581	.....	Diffuse
5371.734......	6	9 comps.?	2	0.413 W_2	W_2	1.431	.....	*n*-comps. fringed. Probably 6 *n*-, 3 *p*-comps.
5383.578......	4	Triple?	3	0.480 W_1	W_1	1.656	.....	
5393.375......	3	Triple	2	0.673	.....	2.314	.....	
5397.344......	6	Sextuple?	2, 3	0.630 W_2	0.222	2.163	0.762	
5404.357......	5	Triple?	2	0.467 W_1	W_1	1.599	.....	Diffuse
5405.989......	6	9 comps.?	2, 2	Pair II, 0.461 (1) Pair I, 0.222 (4)	0.117 (2) 0.000 (3) 0.121 (2)	1.577 0.760	0.400 0.000 0.414	Probably third pair *n*-comps. outside
5411.124......	3	Triple?	2	0.435 W_1	W_1	1.486	.....	Diffuse
5415.416......	5	Triple?	2	0.510 W_1	W_1	1.739	.....	Diffuse
5424.290......	5	Triple?	2	0.498 W_1	W_1	1.693	.....	Diffuse

5429.911......	6	10 comps.?	2, 3	0.607 w_2	0.300	2.059	1.017	3 or possibly 4 pairs *n*-comps. Probably weak inner pair *p*-comps.
5434.740......	5	Unaffected	..	.....	.....	.....	.....	
5445.259......	2	Triple?	2	0.415	w_1	1.399	.....	Diffuse
5447.130......	5	12 comps.	2, 3	Pair IV, 0.874 (1)	Pair II, 0.477 (6)	2.946	1.507	*n*-comps. barely resolved
				Pair III, 0.701 (2)	Pair I, 0.226 (1)	2.363	0.762	
				Pair II, 0.477 (2)	.....	1.608	.....	
				Pair I, 0.219 (1)	.....	0.738	.....	
5455.834......	4	Quintuple	2, 3	0.347 (1)	0.680	1.163	2.283	Central line of *n*-triplet displaced 0.009 Å toward red from normal
				0.000 (2)	.....	0.000	....	
				0.345 (1)	.....	1.160	.....	
6136.829......	5	Triple	3	0.515	.....	1.367	.....	
6137.915......	5	Triple	3	0.654	.....	1.736	.....	
6141.938......	1	Triple?	2	1.017	w_1	2.696	.....	Faint
6148.040......	1	Sextuple?	1	0.649 w_2	w_1	1.717	.....	Very diffuse
6149.458......	1	Quadruple	1, 1	0.812	0.740	2.148	1.950	Enhanced line
6157.945......	1	Triple?	2	0.719	w_1	1.896	.....	
6165.577......	1	Sextuple?	..	n.m.w_2	w_2	.....	.....	*n*-comps. diffuse
6170.730......	1	Sextuple?	2	0.725 w_2	w_3	1.904	.....	*p*-comp. almost resolved
6173.553......	1	Triple	2	1.590	.....	4.171	.....	Difficult. Blend with air band
6180.420......	1	Triple?	..	n.m.	w_1	.....	.....	Faint
6188.210......	1	Triple	..	n.m.	.....	.....	.....	Faint
6191.779......	5	Triple	3	0.541	.....	1.411	.....	
6200.527......	1	Sextuple?	1	1.026 w_2	w_3	2.669	.....	Comps. diffuse
6213.644......	1	Sextuple	2, 3	Pair II, 1.603 (1)	0.572	4.151	1.481	
				Pair I, 0.798 (1)	.....	2.067	.....	
6215.360......	1	Triple	2	0.583	.....	1.509	.....	
6219.494......	1	Sextuple?	2, 2	0.991 w_2	0.385	2.562	0.995	
6230.943......	6	Triple	3	0.767	.....	1.976	.....	
6232.856	1	Sextuple?	2	1.205 w_1	w_2	3.102	.....	
6238.598.	1	Sextuple?	1, 1	1.042 w_1	0.512	2.677	1.315	Enhanced line
6246.535......	2	Sextuple?	2, 2	0.958 w_1	0.278	2.456	0.713	

TABLE I—*Continued*

λ	Intensity	Character of Separation	Weight	Δλ		Δλ/λ²		Remarks
				n-Components	*p*-Components	*n*-Comp.	*p*-Comp.	
6247.774......	1	Septuple ?	1	0.670 w_2	w_3	1.716	.....	Enhanced line. *n*-comps. very diffuse. Probably 3 *p*-comps.
6252.773......	3	Triple	3	0.582	.....	1.488	.....	
6254.456......	1	Triple	3	0.952	.....	2.434	.....	
6256.572......	1	Sextuple ?	–, 2	n.m.w_3	0.696	.....	1.778	*n*-comps. very diffuse
6265.348......	1	Sextuple ?	2, 2	0.969 w_2	0.278	2.469	0.708	
6270.442......	1	Triple ?	..	n.m.	w_1	.....	.....	Very faint
6291.184......	1	Sextuple ?	1	1.014	w_2	2.562	.....	
6298.007......	1	Sextuple ?	..	n.m.w_2	w_3	.....	.....	
6301.718......	3	Sextuple ?	2, 2	1.063 w_2	0.392	2.676	0.987	*n*-comps. probably double
6302.709......	1	Triple	2	1.618	.....	4.073	.....	
6315.517......	1	Sextuple ?	1	0.906 w_1	w_2	2.271	.....	Faint. *p*-comp. almost resolved. Enhanced line
6318.239......	3	Triple	2	0.452	.....	1.132	.....	
6322.907......	1	Triple	2	0.965	.....	2.414	.....	
6331.067......	1	Sextuple ?	1	0.820 w_2	w_1	2.046	.....	Very faint
6335.554......	3	Septuple ?	2	0.665 w_2	w_3	1.656	.....	Probably 3 *p*-comps.
6337.048......	3	Sextuple	2, 2	Pair II, 1.641 (1)	0.632	4.086	1.574	
				Pair I, 0.946 (1)	.....	2.356	.....	
6339.096......	1	Triple ?	..	n.m.	.....	.....	.....	Very faint
6344.371......	1	Sextuple ?	1	0.771 w_1	n.m.	1.916	.....	Very faint. *p*-comp. double
6355.246......	1	Triple	1	0.730	.....	1.808	.....	Very faint
6358.898......	1	Sextuple ?	1	0.746 w_2	w_1	1.845	.....	Very faint
6380.958......	1	Triple	1	0.464	.....	1.140	.....	Enhanced line
6393.820......	8	Triple	2	0.593	.....	1.450	.....	
6400.217......	9	Septuple ?	2	0.802 w_1	w_2	1.958	.....	*n*-comps. slightly fringed. Probably 3 close *p*-comps.

6408.233......	1	Septuple?	–, 2	n.m.	0.343 (1) 0.000 (2) 0.349 (1)	....	0.837 0.000 0.852	Apparently 4 weak *n*-comps. about equally spaced
6411.865......	5	Septuple?	2	0.686 W_2	W_3	1.668	.....	*n*-comps. fringed, probably 3 *p*-comps.
6417.133......	1	?	1	1.018 W_2	W_3	2.472	.....	*n*- and *p*-comps. very diffuse. Enhanced line
6420.169......	1	Sextuple?	1	0.743 W_2	W_2	1.802	.....	*n*-comps. diffuse. Enhanced line
6421.570......	2	Triple	3	0.993	.....	2.408	.....	
6431.066......	3	Sextuple?	2	0.775 W_1	W_1	1.873	.....	

TABLE II

MEASUREMENTS OF ZEEMAN EFFECT FOR TITANIUM

λ	INTENSITY	CHARACTER OF SEPARATION	WEIGHT	$\Delta\lambda$		$\Delta\lambda/\lambda^2$		REMARKS
				n-Components	p-Components	n-Comp.	p-Comp.	
4278.390	2	Triple	3	0.304	.....	1.661	.....	
4281.530	2	Octuple	3, 3	0.444 (4)	0.222 (2)	2.422	1.211	
				0.218 (2)	0.000 (3)	1.189	0.000	
				0.000 (1)	0.224 (2)	0.000	1.222	
				0.218 (2)	.....	0.189	.....	
				0.448 (4)	.....	2.443	.....	
4282.860	3	Triple	3	0.244	.....	1.330	.....	
4285.164	5	Quadruple ?	3	0.566	W_1	3.083	.....	
4286.168	4	Sextuple ?	2, 3	0.400 W_2	0.166	2.177	0.904	
4287.566	4	Sextuple ?	2, 3	0.421 W_2	0.146	2.290	0.794	
4288.038	2	Septuple ?	2	0.516 W_2	W_3	2.806	.....	n-comps. have inner fringes. Probably 3 p-comps.
4289.237	4	12 comps.	2, 3	Pair IV, 0.586 (1)	Pair II, 0.286 (6)	3.186	1.566	
				Pair III, 0.443 (2)	Pair I, 0.140 (1)	2.408	0.761	
				Pair II, 0.306 (2)	.....	1.663	.....	
				Pair I, 0.144 (1)	.....	0.783	.....	
4290.377	10	?	2	0.284 W_2	W_3	1.543	.....	n-comps. strongly fringed 3 or more p-comps. Enhanced line
4291.114	2	Quintuple	3, 3	0.221 (1)	0.445	1.200	2.417	
				0.000 (2)	.....	0.000	.....	
				0.220 (1)	.....	1.195	.....	
4291.375	2	Triple	1	0.230	.....	1.249	.....	Difficult blend with 4291.114
4294.204	10	Triple	3	0.361	.....	1.958	.....	Enhanced line
4295.914	4	Unaffected	..	.....	.....	.....	.....	
4298.828	4	Septuple	2, 3	Pair II, 0.292 (1)	0.060 (2)	1.580	0.325	p-comps. distinctly unsymmetrical
				Pair I, 0.145 (5)	0.000 (3)	0.784	0.000	
					0.086 (2)	.....	0.465	

4299.410	3	Quadruple ?	1	0.430	W_2	2.327	.....	
4299.803	2	Triple ?	1	0.356	W_1	1.925	.....	
4300.211	8	?	2	0.367 W_1	W_2	1.985	.....	*n*-comps. fringed. 3 or more *p*-comps. Enhanced line
4300.732	2	Septuple ?	2	0.265 W_1	W_2	1.432	.....	*n*-comps. fringed, probably 3 *p*-comps.
4301.158	3	Triple ?	3	0.350	W_1	1.892	.....	
4302.085	5	Sextuple	3, 3	Pair II, 0.585 (1)	0.216	3.161	1.167	Enhanced line
				Pair I, 0.151 (3)	.....	0.816	.....	
4306.078	8	Septuple ?	2	0.367 W_1	W_2	1.979	.....	*n*-comps. fringed, probably 3 *p*-comps.
4308.081	8	Octuple	2, 2	Pair III, 0.588 (1)	0.236	3.168	1.272	Blend with iron impurity line probably gives apparent dissymmetry in intensity of *n*-comps. Enhanced line
				Pair II, 0.442 (2)	.....	2.382	.....	
				Pair I, 0.291 (3)	.....	1.568	.....	
4311.880	1	Sextuple ?	2	0.147	W_1	0.791	.....	Outer pair *n*-comps. not measurable. Possibly 3 *p*-comps. Blend with faint lines
4313.034	8	Sextuple ?	2, 2	0.449 W_2	0.159	2.414	0.855	Enhanced line
4314.964	3	Triple	3	0.424	.....	2.277	.....	
4315.138	5	Quadruple	3, 3	0.392	0.349	2.105	1.874	Enhanced line
4316.962	2	Triple	3	0.207	.....	1.111	....	Enhanced line
4318.817	3	Triple	3	0.337	.....	1.807	.....	
4321.119	3	Sextuple	3, 3	Pair II, 0.785 (2)	0.261	4.204	1.398	Enhanced line
				Pair I, 0.257 (1)	.....	1.376	.....	
4321.813	3	Triple	3	0.310	.....	1.660	.....	
4323.531	1	Triple	2	0.464	.....	2.482	.....	
4325.306	3	Triple	3	0.301	.....	1.609	.....	
4326.520	2	Triple	3	0.403	.....	2.152	.....	
4330.405	3	Sextuple?	2	0.415 W_1	W_2	2.213	.....	Enhanced line
4330.866	3	?	2	0.654 W_2	W_3	3.487	.....	Enhanced line. *n*-comps. have inner fringes
4338.084	10	Triple	3	0.247	.....	1.312	.....	Enhanced line

TABLE II—*Continued*

λ	Intensity	Character of Separation	Weight	Δλ		Δλ/λ²		Remarks
				n-Components	*p*-Components	*n*-Comp.	*p*-Comp.	
4468.663	15	Triple	3	0.340	.....	1.702	.....	Enhanced line
4469.316	1	Triple	2	0.426	.....	2.133	.....	
4471.017	2	10 comps.?	2, 2	Pair III, 0.724 (1)	0.458	3.622	2.292	Trace of inner pair *p*-comps.
				Pair II, 0.386 (1)	.....	1.931	.....	
				Pair I, 0.126 (1)	.....	0.630	.....	
4471.408	2	9 comps.	2, 2	Pair III, 0.826 (1)	0.113 (2)	4.132	0.565	
				Pair II, 0.613 (2)	0.000 (3)	3.066	0.000	
				Pair I, 0.364 (4)	0.116 (2)	1.821	0.580	
4475.026	2	Septuple?	2	0.509 W_1	W_3	2.542	.....	Probably 4 *n*-, 3 *p*-comps.
4479.879	2	Triple	3	0.829	.....	4.130	.....	
4480.752	1	Triple	2	0.611	.....	3.043	.....	
4481.438	3	Triple	3	0.548	.....	2.729	.....	
4482.904	2	Sextuple?	2	0.498 W_1	W_2	2.478	.....	
4488.493	6	Triple	3	0.355	.....	1.762	.....	Enhanced line
4489.262	3	9 comps.	2, 2	Pair III, 0.858 (1)	0.111 (2)	4.258	0.551	Compare λ 4471.408
				Pair II, 0.597 (2)	0.000 (3)	2.963	0.000	
				Pair I, 0.382 (4)	0.110 (2)	1.896	0.546	
4495.182	1	Triple	1	0.353	.....	1.747	.....	
4496.318	3	Triple	3	0.493	.....	2.439	.....	
4497.842	1	Triple	2	0.534	.....	2.639	.....	
4501.445	15	Triple	3	0.298	.....	1.471	.....	Enhanced line
4512.906	4	Triple	3	0.501	.....	2.460	.....	
4518.198	4	Quadruple?	3	0.498	W_1	2.440	.....	
4518.866	1	Triple	2	0.220	.....	1.077	.....	
4522.974	4	Sextuple?	3	0.502 W_1	W_2	2.454	.....	
4527.490	4	Octuple	3, 3	0.324 (7)	0.164 (1)	1.581	0.800	
				0.162 (2)	0.000 (2)	0.790	0.000	
				0.000 (1)	0.165 (1)	0.000	0.805	
				0.166 (4)	.....	0.810	.....	
				0.338 (7)	.....	1.649	.....	
4529.656	2	Sextuple?	2, 2	0.358 W_2	0.278 W_1	1.745	1.355	Enhanced line

4533.419......	5	Triple	3	0.469	.....	2.282	.....	
4534.139......	6	Triple ?	2	0.360 W_1	W_1	1.751	.....	*n*-comps. slightly fringed. Enhanced line
4534.953......	4	Triple	3	0.449	.....	2.183	....	
4535.741......	3	Triple	3	0.424	.....	2.061	.....	
4536.094......	3	Triple	2	0.323	.....	1.570	.....	
4536.222......	3	Unaffected ?	..	.....	.....	.....	.....	No resolution. Blend with 36.094 may conceal slight widening of *n*-comp.
4537.389......	1	Triple	1	0.355	.....	1.725	.....	
4544.190......	1	Quadruple ?	1	0.308	W_2	1.492	.....	
4544.864......	3	Octuple	3, 3	0.334 (7)	0.171 (1)	1.617	0.828	Comps. in all respects similar to 4427.490
				0.168 (2)	0.000 (2)	0.813	0.000	
				0.000 (1)	0.166 (1)	0.000	0.804	
				0.170 (4)	.....	0.823	.....	
				0.332 (7)	.....	1.607	.....	
4548.938......	3	Septuple ?	2	0.560 W_1	W_2	2.706	.....	*n*-comps. have inner fringes. Probably 3 *p*-comps.
4549.808......	20	Triple	3	0.440	.....	2.125	.....	Enhanced line
5016.340......	7	Sextuple ?	2, 3	0.543	0.214	2.158	0.851	
5020.208......	8	Octuple ?	2, 3	0.507 W_3	0.276	2.012	1.095	Probably 3 pairs *n*-comps.
5023.052......	8	12 comps. ?	2, 3	0.466 W_3	0.370 W_3	1.847	1.466	Probably 4 pairs *n*-comps. *p*-comps. have inner fringes.
5025.027......	7	10 comps.	2, 2	Pair III, 0.684 (1)	Pair II, 0.546 (6)	2.709	2.162	
				Pair II, 0.416 (2)	Pair I, 0.269 (1)	1.647	1.065	
				Pair I, 0.133 (4)	.....	0.527	.....	
5025.749......	5	Triple	3	0.471	.....	1.865	.....	
5036.089......	10	Triple	3	0.455	.....	1.794	.....	
5036.645......	8	Triple	3	0.436	.....	1.718	.....	
5038.579......	8	Triple	3	0.340	.....	1.339	.....	
5040.138......	8	Triple	3	0.404	.....	1.590	.....	
5053.056......	3	Triple ?	2	0.449	W_1	1.759	.....	

TABLE II—*Continued*

λ	INTENSITY	CHARACTER OF SEPARATION	WEIGHT	$\Delta\lambda$		$\Delta\lambda/\lambda^2$		REMARKS
				n-Components	*p*-Components	*n*-Comp.	*p*-Comp.	
5062.285......	3	Triple?	2	0.412	W_1	1.608	.....	
5064.244......	1	Triple	..	n.m.	.....	.....	.....	Very faint
5064.836......	8	Triple	3	0.463	.....	1.805	.....	
5066.174......	1	Sextuple?	–,1	n.m.W_3	0.407	.....	1.586	
5069.592......	1	Triple	2	0.235	.....	0.914	.....	
5071.666......	4	Sextuple?	1, 1	0.470 W_2	0.275	1.827	1.069	
5072.479......	6	Triple	3	0.502	.....	1.951	.....	Enhanced line
5087.239......	4	Triple	3	0.329	.....	1.271	.....	
5113.617......	5	Triple	3	0.431	.....	1.648	.....	
5120.592......	7	Triple	3	0.434	.....	1.655	.....	
5129.336......	8	Triple	3	0.478	.....	1.812	.....	Enhanced line
5145.636......	6	Triple	3	0.493	.....	1.862	.....	
5147.652......	5	Septuple?	2	0.805 W_2	W_3	3.038	.....	Probably more than 7 comps. *p*-comps. almost resolved
5152.361......	5	Quadruple?	3	0.671 W_1	W_1	2.528	.....	
5154.244......	4	Sextuple?	2	0.666 W_2	W_2	2.507	.....	Enhanced line
5173.917......	10	Triple	2	0.292	.....	1.091	.....	
5186.073......	8	Triple	3	0.385	.....	1.432	.....	Enhanced line
5188.863......	12	Triple	3	0.512	.....	1.902	.....	Enhanced line
5193.139......	10	Triple	3	0.468	.....	1.735	.....	
5201.260......	3	Triple?	2	0.648 W_1	W_1	1.396	.....	
5206.215......	4	Triple	2	0.470	.....	1.734	.....	
5210.555......	10	Triple	3	0.547	.....	2.014	.....	
5219.875......	4	Sextuple?	2	0.326 (2)	W_2	1.191	.....	Unsymmetrical. Probably 4 *n*-comps., 2 violet blended, 2 red separated. *p*-comp. displaced 0.062 to violet from normal. All comps. measured from normal
				normal	.....	.....	.....	
				0.264 (1)	.....	0.969	.....	
				0.400 (1)	.....	1.468	.....	
5222.849......	3	Unaffected	..	.....	.....	.....	.....	

5866.675......	10	Triple	3	0.674	.....	1.958	.....	
5880.490......	3	Triple	3	0.830	.....	2.401	.....	
5899.518......	7	Triple	3	0.656	.....	1.885	.....	
5903.555......	2	Triple	2	0.876	.....	2.513	.....	
5918.773......	3	Triple	3	0.882	.....	2.518	.....	Red comp. strongest?
5922.334......	5	Triple	2	0.312	.....	0.890	.....	
5938.035......	2	Sextuple?	2, 1	0.840 w_2	0.226	2.382	0.641	*p*-comp. scarcely resolved
5941.985......	5	Sextuple	2, 2	Pair II, 0.905 (2)	0.547	2.563	1.549	
				Pair I, 0.295 (3)	.....	0.836	.....	
5953.386......	8	Triple	3	0.637	.....	1.798	.....	
5966.055......	7	Triple	3	0.590	.....	1.617	.....	
5978.768......	7	Triple	3	0.533	.....	1.491	.....	
5999.920......	2	Quadruple?	2	0.823 w_1	w_2	2.286	.....	
6064.853......	2	Triple	3	1.159	.....	3.151	.....	
6085.470......	4	Sextuple?	2, 2	1.001 w_2	0.307	2.703	0.829	
6091.395......	6	Triple	3	0.679	.....	1.830	.....	
6093.030......	1	Triple	2	0.755	.....	2.034	.....	
6098.870......	2	Triple?	2	0.563 w_1	w_1	1.514	.....	
6121.215......	1	Triple	2	0.622	.....	1.660	.....	
6126.435......	5	Septuple?	2	0.706 w_1	w_3	1.881	.....	*n*-comps. fringed. Probably 3 *p*-comps.
6146.445......	1	Triple	2	0.476	.....	1.260	.....	
6149.950......	1	Triple	2	0.698	.....	1.845	.....	
6215.630......	3	Triple	3	0.697	.....	1.804	.....	
6220.700......	2	Triple	2	0.618	.....	1.597	.....	
6221.552......	1	Triple	2	0.511	.....	1.320	.....	
6258.322......	10	Triple	2	0.661	.....	1.688	.....	Red *n*-comps. of first line blended with violet comp. of second
6258.927......	12	Triple	2	0.714	.....	1.823	.....	
6261.316......	10	Triple	3	0.556	.....	1.418	.....	
6303.985......	5	Octuple?	2, 2	0.565 w_3	0.554	1.422	1.394	*n*-comps. very wide and diffuse. Probably at least 3 pairs
6312.456......	5	Octuple?	2, 2	0.766 w_3	0.463 w_1	1.923	1.162	*n*-comps. wide, not so diffuse as 6304. Probably 3 pairs. Possibly 4 *p*-comps.

EXPLANATION OF THE PLATES

Enlargements of selected portions of the iron and titanium spectra are reproduced in Plates V–VIII. In Plate V, the spectra of the spark without magnetic field is placed above and below, while the three magnetic-field spectra are those given when the light is observed across the lines of force with a Nicol in two positions 90° apart, and without a Nicol, the first two giving the *p*- and *n*-components respectively, while the last gives the two superposed.

For the other plates, the same plan is followed, but only the spectra showing the *p*- and *n*-components are presented. The four spectra in Plate VII show two portions of the titanium spectrum, the range of intensity among the lines being so great that one photograph can do justice only to a certain set.

The number of lines for each type of separation, including both the clear and the questioned cases as given in the complete tables, is shown in Table III.

The publication discusses in detail the characteristics of each type.

RELATION OF SEPARATIONS TO THE NORMAL INTERVAL

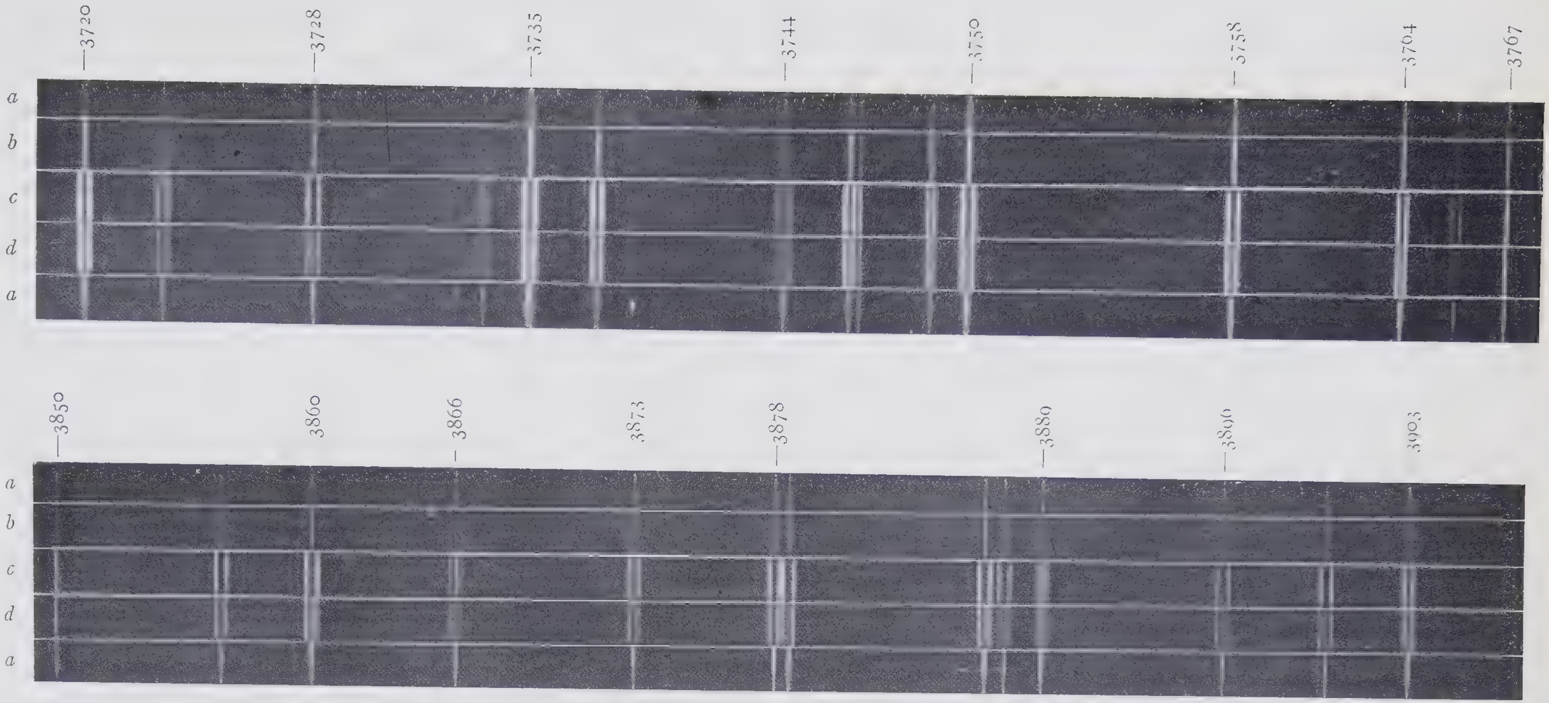
The study of how generally the separations observed show a simple relation to a fundamental interval has been gone into with some detail. The relation

$$a=\frac{\Delta\lambda}{\lambda^2}=\frac{e}{m}\cdot\frac{H}{4\pi v},$$

where e/m is the ratio of charge to mass of the electron, H the field-strength, and v the velocity of light, gives values for a of 0.753 and 0.812 for the field-strengths corresponding to the measurements for iron and titanium, respectively. The "normal triplet" should then show values of $\Delta\lambda/\lambda^2$ for the distance between the side components of about 1.500 and 1.600, respectively.

Various types of separation are considered in turn with regard to how nearly the measured separations can be expressed in terms of the normal interval a. In the iron spectrum, 272 clear triplets were measured, i.e., triplets whose components show no widening which would indicate that the line is of higher type. Of these, 230

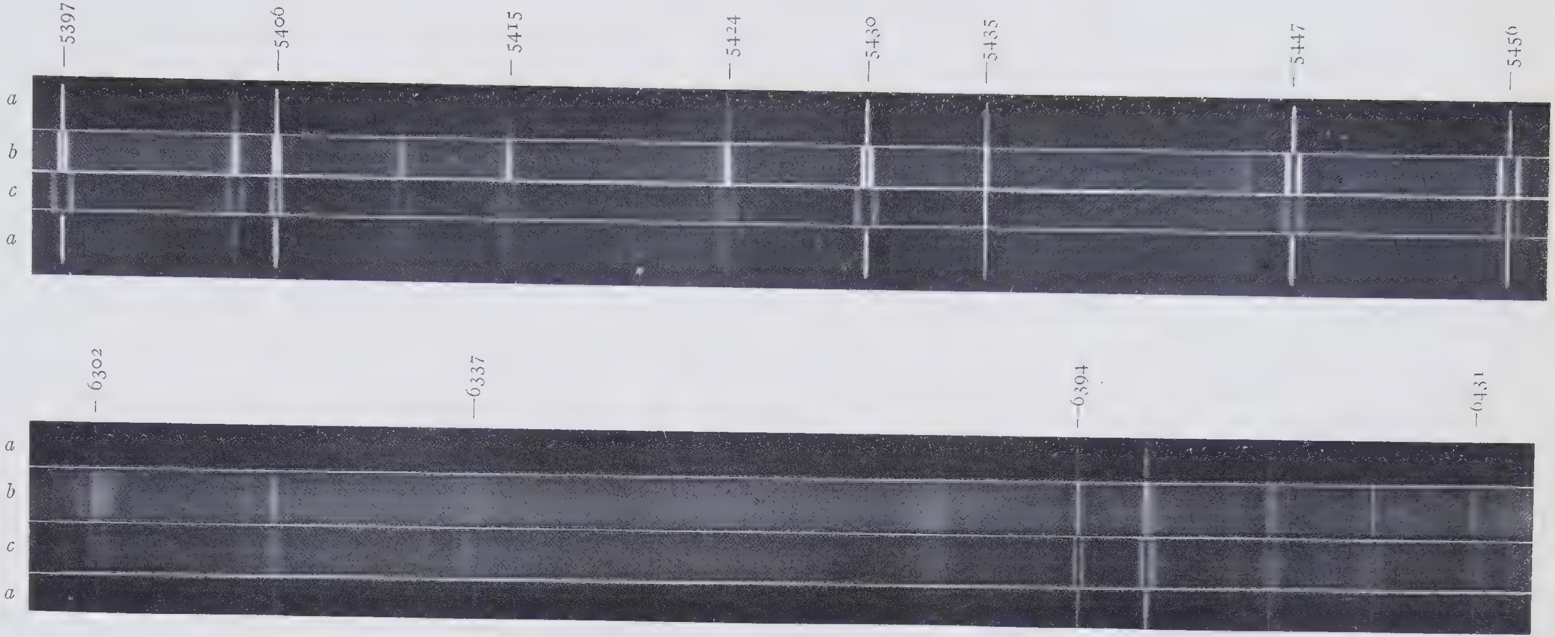
PLATE V



EFFECT OF MAGNETIC FIELD ON THE SPECTRUM OF IRON

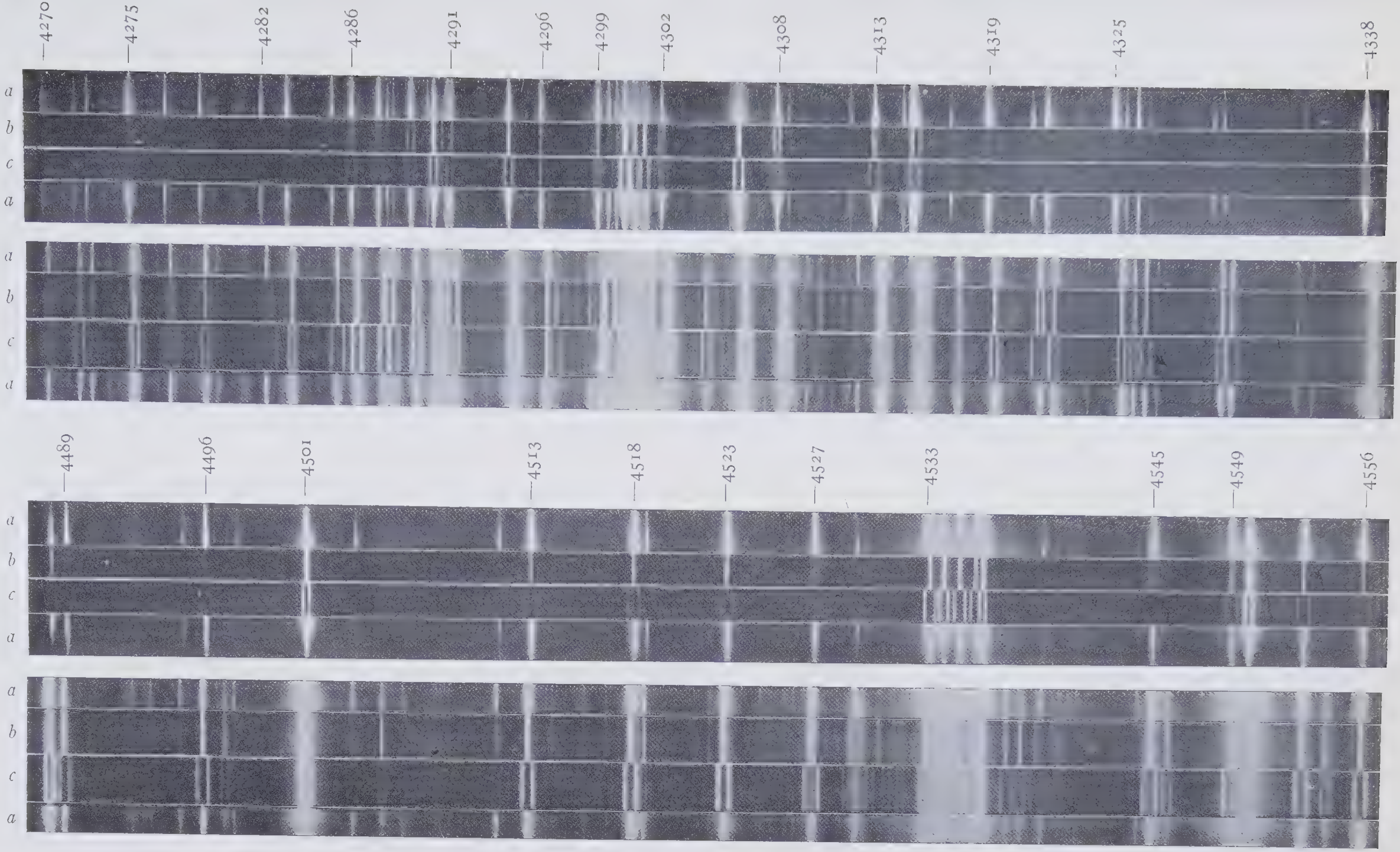
a. Spark without field. *b*. *p* Components. *c*. *n* Components. *d*. Spectrum without Nicol, *n*- and *p*-Components superposed

PLATE VI



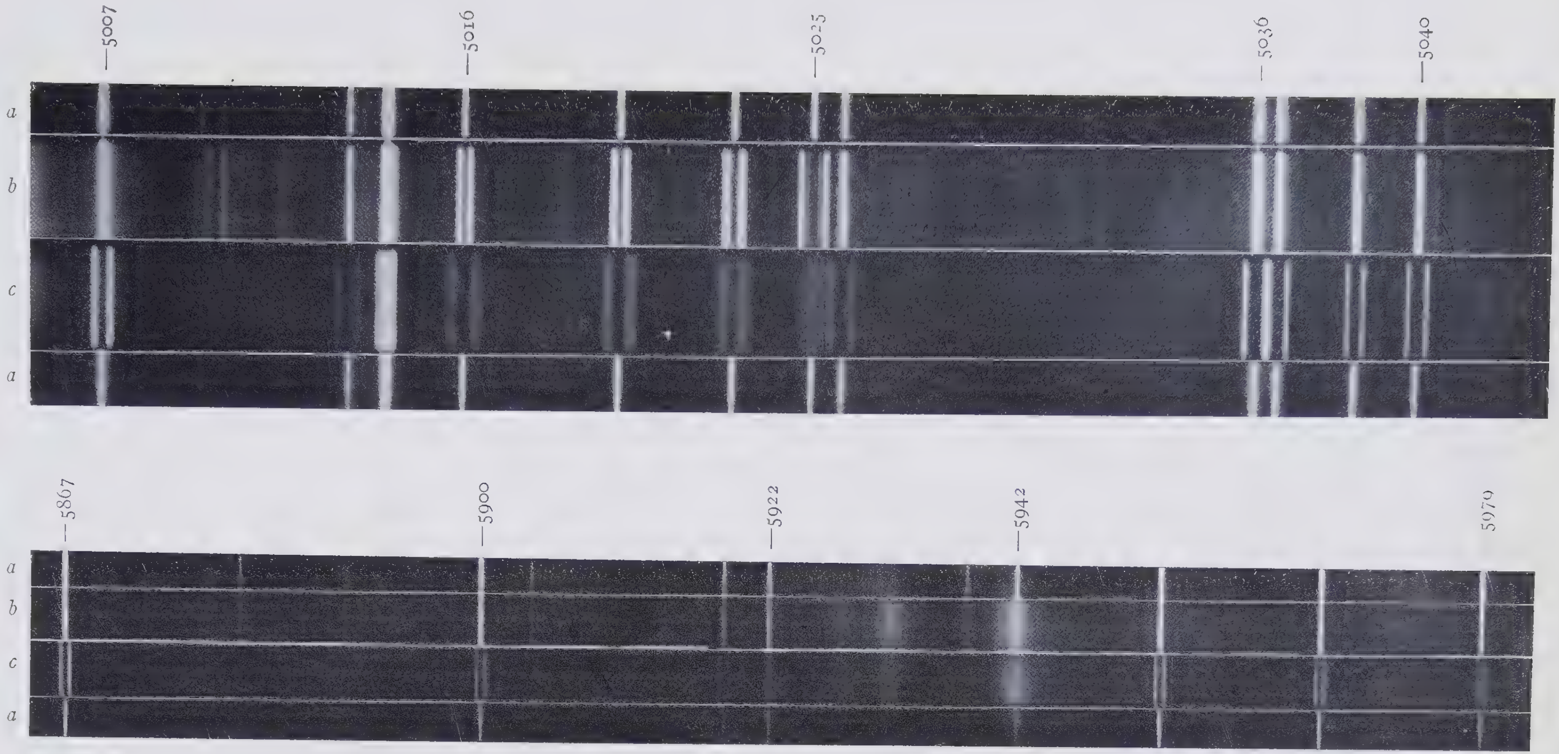
Effect of Magnetic Field on the Spectrum of Iron

a. Spark without field. *b*. *p*-Components. *c*. *n*-Components



Effect of Magnetic Field on the Spectrum of Titanium
Experimental conditions varied to bring out both strong and weak lines
a. Spark without field. *b*. *p*-Components. *c*. *n* Components

PLATE VIII



Effect of Magnetic Field on the Spectrum of Titanium

a. Spark without field. *b*. *p*-Components. *c*. *n*-Components

gave separations which could be expressed readily as multiples of $a/2$, 54 showing a value of $\Delta\lambda/\lambda^2$ close to $2a$, and 72 close to $3a$. The titanium table contains 242 clear triplets, 145 of which gave multiples of $a/2$, 73 of these being normal triplets. Many of the remaining triplets allow their separations to be expressed as even multiples of $a/4$, but, with the fields employed, this brings the unit close to the possible error of measurement, except for lines of high weight.

TABLE III

Summary of Types of Separation

Separation	Iron	Titanium
Unaffected	9	4
Triple	393	291
Quadruple	49	28
Quintuple	7	5
Sextuple	118	77
Septuple	37	12
Octuple	6	11
9 components	9	3
10 components	7	7
11 components	2	2
12 components	4	2
13 components	2	0
Unclassified	19	16
Total	662	458

The lines appearing as quadruplets (in many cases really sextuple owing to two pairs of n-components being blended) in the majority of cases allow their separations to be expressed as multiples of a or $a/2$, the most common ratios of n- and p-separations being $2a:a$ and $3a:a$.

The lines of more complex type which are fully resolved, ranging from quintuplets to 12-component lines, are tabulated in a form to show how the separations may be expressed in terms of the normal interval and also to give the ratio, usually very simple, between the successive separations. Fifty-seven complex lines are thus treated, and in almost every case the ease with which the separations can be expressed in terms of a leaves no doubt as to the generality of a relation of this sort. As an example, the 12-component lines λλ 3722.729, 3872.639, and 5447.130 of iron, and 4289.237 of titanium, some of which are given in Tables I and II in this abstract, present in each case the following arrangement of the six pairs of components:

$\pm 2a$	n	4
$3a/2$	n	3
a	n,p	2
$a/2$	n,p	1

The ratio separations for successive pairs is thus 1:2:3:4. Not all lines show so simple a ratio, and probably a much stronger field, permitting the use of small fractional parts of a, would cause some revision of the relations here given for a few lines. The results in general, however, are fully in accordance with the rule given by Runge[1] that for complex lines the distances of the various components from the center may be expressed as multiples of aliquot parts of a.

This treatment of complex separations has brought to notice many cases of "magnetic duplicates," lines showing exactly the same structure and with the same intervals between components. The knowledge of the structure of these lines may be of service in the search for series relations, but as yet nothing definite in this direction has been developed.

DISSYMMETRY

The number of lines showing clear dissymmetry in spacing or intensity of components is not large, fourteen such lines being listed for the two spectra.

Measurements were made for a number of sharp iron triplets to test the dissymmetry predicted by Voigt and investigated by Zeeman and others, according to which the violet component of a triplet should have a slightly greater spacing from the central component, while the red component should be slightly stronger than the violet. Of 26 lines favorable for this purpose, all but 3 show a larger spacing for the violet component, while most of the lines show a difference considerably greater than the probable error of measurement. Numerous triplets also appear for which the red component is very slightly stronger than the violet. A detailed study must wait until a much greater field-strength is available, but this preliminary examination indicates that the effect is real for many triplets.

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[1] *Physikalische Zeitschrift*, **8**, 232, 1907.

LAW OF CHANGE OF THE AVERAGE SEPARATION OF THE *n*-COMPONENTS WITH THE WAVE-LENGTH

The extensive range of wave-length studied for iron and titanium, together with the large number of lines measured, has furnished material for a statistical study of the change of the average separation with the wave-length. The method of treatment has been to obtain the mean value of $\Delta\lambda/\lambda^2$ for the *n*-components of lines for each 500 Å from λ 3700 to λ 6700. When there are two or more pairs of *n*-components the mean of the separations is taken. The averages thus obtained are presented in Table IV. The means for the six groups of 500 Å are given first, then the means for the three groups of 1000 Å. These latter are the means for the whole number of lines included in the range, not the average of the means for the 500-groups.

TABLE IV

MEANS OF $\Delta\lambda/\lambda^2$ (*n*-COMPONENTS) FOR SUCCESSIVE REGIONS OF WAVE-LENGTH

RANGE OF λ	IRON		TITANIUM	
	No. Lines	Mean $\Delta\lambda/\lambda^2$	No. Lines	Mean $\Delta\lambda/\lambda^2$
3700–4200....	267	2.003	80	1.909
4200–4700....	101	2.051	152	2.027
4700–5200....	74	2.125	81	1.684
5200–5700....	62	1.932	47	1.819
5700–6200....	37	1.837	34	1.942
6200–6700....	41	2.131	28	1.764
3700–4700....	368	2.016	232	1.986
4700–5700....	136	2.037	128	1.734
5700–6700....	78	1.989	62	1.862

The close agreement of the means shows that there is an approximate constancy of the values of $\Delta\lambda/\lambda^2$ for different parts of the spectrum. Taking the successive means of the 500-groups, the average value for iron is 2.013, for titanium 1.858. The largest deviation from the mean for any group is 8.7 per cent for iron and 9.4 per cent for titanium. For neither element is there any systematic change of the means for successive groups.

The means for the groups of 1000 Å show a still closer agreement, the largest deviation from the mean of these groups being only 1.2 per cent for iron and 6.8 per cent for titanium.

The mean values for titanium run smaller than those for iron, although the titanium measurements correspond to the greater field-strength. When a number of spectra are examined in this way, it may prove that this difference is connected with certain properties of the elements concerned.

This constancy of the mean values of $\Delta\lambda/\lambda^2$ appears to be based on the general relation of the separations to the fundamental interval a, and to result from the fact that the great majority of the separations for the n-components range from the values of $2a$ to $3a$. Among triplet lines, the greater number show a separation larger than $2a$. The exceptionally large and small values for triplets, together with the mean separations of the complex lines, combine to form a fairly definite mean which holds for the whole range of spectrum examined.

Since $\Delta\lambda/\lambda^2$ is thus shown to be nearly constant, it may be said that *for the spectra of iron and titanium and probably for spectra in general, the mean separation of the n-components varies as the square of the wave-length.* A similar rule must hold for the p-components, since complex lines of the same structure in different parts of the spectrum show the same relation to the interval a.

A result obtained by a different method, but doubtless based on the same general relation, was given by Mr. Hale[1] in a comparison of sun-spot doublets with Zeeman separations on laboratory plates. He observed that the mean $\Delta\lambda$ divided by the square of the mean λ agreed exactly for two regions of the iron spectrum.

THE EFFECT OF THE MAGNETIC FIELD UPON ENHANCED LINES

In my former paper on the titanium spectrum, as well as in the recent papers of Mr. Babcock[2] on the Zeeman effect for chromium and vanadium, the conclusion was reached that the enhanced lines as a class are not affected differently from the non-enhanced lines of these elements. The larger amount of material in the present publication has verified this conclusion in general, but it also presents evidence that the stronger enhanced lines of titanium show a tendency toward one type. The question is of interest because the enhanced lines form a fairly well-defined class, requiring certain physical conditions of the light-source for their production, and a modification of these conditions affects the intensity and appearance of all such lines in the same way though in different degrees.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 30; *Astrophysical Journal*, **28**, 315, 1908.

[2] *Contributions from the Mount Wilson Solar Observatory*, Nos. 52 and 55; *Astrophysical Journal*, **33**, 217, 1911.

Among the lines measured for magnetic separation in this publication, the ratio of enhanced to non-enhanced lines is about 1:14 for iron and 1:5 for titanium. There appears to be no undue proportion of any one type of separation among the enhanced lines considered as a whole. None of the lines unaffected by the magnetic field are enhanced, and only one quintuplet occurs in this class. The more common types are all well represented among them. However, one noteworthy peculiarity is shown by the enhanced lines of titanium in the region from λ 3600 to λ 4600, rich in this kind of lines. Twenty-two lines occur here which show a high degree of enhancement, and are, as a rule, much stronger in the spark than any of the lines characteristic of the arc. Seventeen of these lines are clear triplets, while in the whole titanium spectrum measured, only a little over half of the lines are clear triplets. The remaining five, which are with one exception the weakest in the list, are of more complex character. As regards magnitude of separation, none of these 17 lines are normal triplets, and they appear to be less closely related to the interval *a* than a like number of triplets taken at random. These data are all presented in tabular form in the complete publication.

COMPARISON OF THE RESULTS FOR THE ZEEMAN EFFECT AND FOR PRESSURE DISPLACEMENT

This subject was treated for the spectra of iron, titanium, and chromium in a former paper.[1] The material for the first two elements is now presented with revised measurements and much more extensive data for titanium, for which I am indebted to Mr. Gale, photographs having been made by him in this laboratory for the titanium arc under pressure. This extension gives 173 iron and 122 titanium lines available for a comparison of magnetic separation and pressure displacement.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 46; *Astrophysical Journal*, **31**, 433, 1910.

The method of treatment of the material in tables is much the same as before, and similar conclusions are reached. The ratios of separation to displacement for different lines show no approach to constancy. In many cases the magnitudes of the two effects are very different, the extreme cases being lines unaffected by the magnetic field which show large pressure displacement. Taking the means of separation and displacement for large numbers of lines in the same region of the spectrum, however, it is found that these means are in general of the same order of magnitude when they are classified broadly as small, medium, and large. This shows that the lines as a rule show some degree of similarity in their response to the two displacing influences. Both effects are observed to increase with the wave-length, although it is not yet established that the rate of increase for the pressure-effect is the same as that for the Zeeman phenomenon, i.e., as the square of the wave-length.

Mount Wilson Solar Observatory
April 10, 1911

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NOTE ON THE GROUPING OF TRIPLET SEPARATIONS PRODUCED BY A MAGNETIC FIELD

By HAROLD D. BABCOCK

In recent papers on the Zeeman effect for chromium[1] and vanadium[2] attention was called by the writer to the grouping of the separations of the outer components of triplet lines. It was shown that for those metals the values of $\Delta\lambda/\lambda^2$ for triplets occur chiefly in two easily distinguishable groups. The completion of tables of magnetic separation for iron and titanium by King[3] has led to further inquiry along this line, which was subsequently extended so as to include all the data available. The additional material here discussed is found in papers by B. E. Moore on zirconium, yttrium, osmium, barium,[4] and thorium;[5] by W. Miller on manganese;[6] by H. M. Reese on nickel;[7] and by R. Jack on tungsten and molybdenum.[8]

The values of $\Delta\lambda/\lambda^2$ for the triplet lines of each metal were arranged in order of magnitude and a curve was drawn showing the frequencies of their occurrence. Lines whose classification or measurement was doubtful were omitted. As a considerable portion of the separations referred to the distance between the outer components instead of between the central and either one of the outer components, all the numbers were reduced to this system and the factor one-half applied at the end. The abscissas for the

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 52; *Astrophysical Journal*, **33**, 217, 1911.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 55; *Astrophysical Journal*, **34**, 1911.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 56; *Astrophysical Journal*, **34**, 1911.

[4] *Astrophysical Journal*, **28**, 1, 1908.

[5] *Ibid.*, **29**, 144, 178, 1909.

[6] *Physikalische Zeitschrift*, **7**, 896, 1906.

[7] *Astrophysical Journal*, **12**, 120, 1900.

[8] Göttingen Dissertation, 1908.

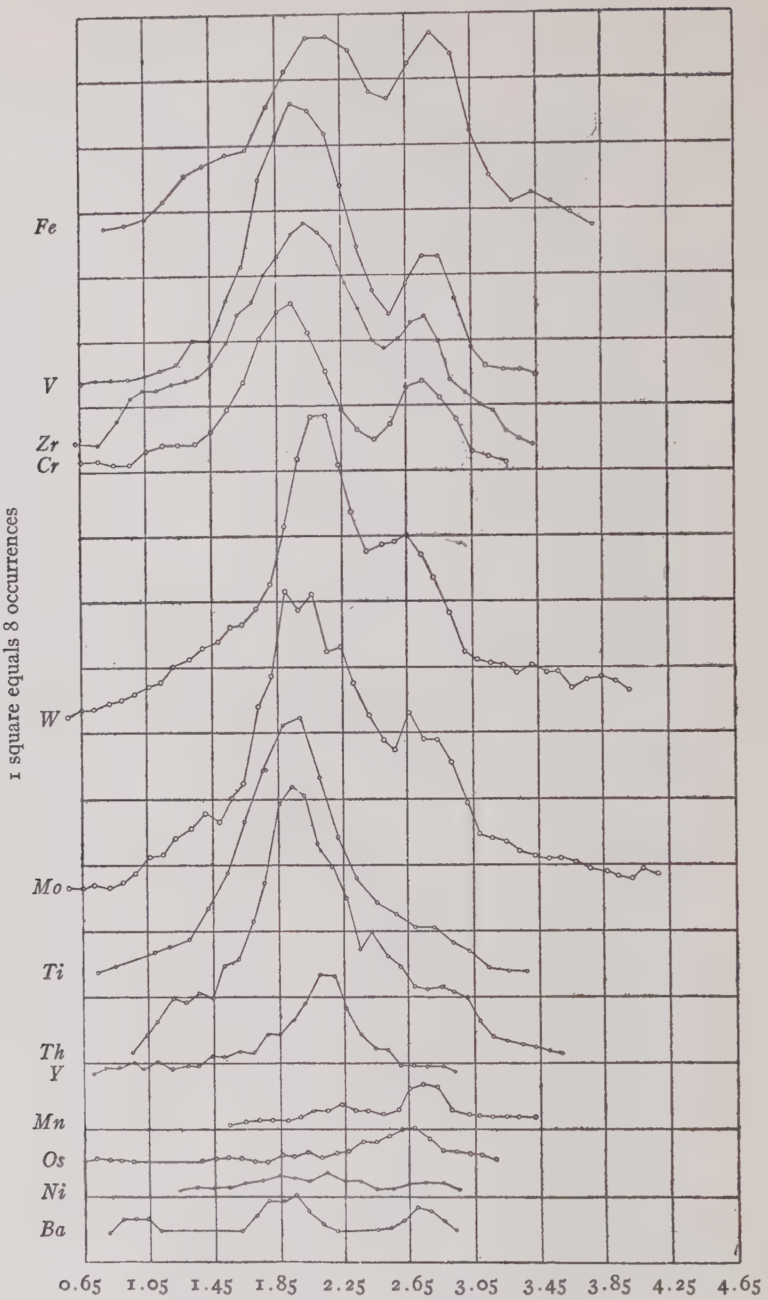

FIG. 1.—Grouping of Triplet Separations
Interval in $\Delta\lambda/\lambda^2$ equals 0.10. Field 20,000 gausses

curves are equal intervals in $\Delta\lambda/\lambda^2$. A given ordinate was obtained by averaging the number of occurrences for its own abscissa with those for the two adjoining ones. As first drawn the curves related to the various field-strengths employed by different observers. The abscissas were accordingly reduced to a standard field of 20,000 gausses, making them directly comparable, and they are thus displayed in Fig. 1. The scales are, for the abscissas: interval in $\Delta\lambda/\lambda^2$ equals 0.10, one square being equal to four intervals; for the ordinates: one square equals eight occurrences.

The alignment of maxima and minima, first noticed for chromium and vanadium, is shown here extending in general to these other metals. The first maxima lie between the limits $\Delta\lambda/\lambda^2=1.80$ and $\Delta\lambda/\lambda^2=2.20$, while the second are included between the values 2.60 and 2.80. The abscissas corresponding to the two maxima are thus seen to have the ratio 2:3. Although some curves show the second maximum only slightly and others have only a suggestion of the first, none exhibits a distinctive grouping except barium. This metal has in addition to the two usual groups a third, the abscissas being in the ratio 1:2:3. Small weight attaches to the curves for osmium, barium, manganese, and nickel on account of the few triplet lines which have been measured in their spectra.

It is to be observed that the data studied here were collected by six observers working in five laboratories, and that the field-strengths were different and were measured by different methods. In addition it is likely that some lines are classified as triplets which are really more complex. So close a similarity among the curves is therefore remarkable, and a combination of the results should be of considerable interest. Accordingly the position of the minimum was carefully determined on each curve and the values of $\Delta\lambda/\lambda^2$ thus divided into two groups. The means for each group, weighted according to the number of lines upon which they depend, when combined yield as values of $\Delta\lambda/\lambda^2$, $1.892\pm0.014_7$ for group I, and $2.794\pm0.018_4$ for group II, the appended numbers being probable errors. Using the equation

$$\frac{\Delta\lambda}{\lambda^2}=\frac{e}{m}\cdot\frac{H}{4\pi v},$$

where H is the field-strength in C.G.S. units and v is the velocity of light, the resulting values of e/m are $1.783 \pm 0.013_8 \times 10^7$ and $2.633 \pm 0.017_4 \times 10^7$, the former being based upon measurements for 2043 triplets and the latter upon those for 827. Two-thirds of the larger value is 1.755 ± 0.116, which, when combined with the first, with weights proportionate to 2043 and 827, yields the final weighted mean 1.775 ± 0.0132. Table I is a summary of the work here indicated.

TABLE I

Grouping of Triplet Separations

Metal	Field	Group I			Group II		
		Limits	Number of Lines	Mean $\frac{\Delta\lambda}{\lambda^2}$ H=20,000	Limits	Number of Lines	Mean $\frac{\Delta\lambda}{\lambda^2}$ H=20,000
Titanium......	17,500	1.00–2.25	214	1.876	2.25–3.20	25	2.872
Iron..........	16,000	1.20–2.00	139	2.079	2.00–2.90	108	2.908
Yttrium........	24,400	1.70–3.10	56	1.955	3.10–4.00	5	2.702
Zirconium......	24,400	1.70–3.00	307	1.821	3.00–4.00	91	2.760
Osmium.......	24,400	1.80–2.60	4	1.843	2.60–4.00	26	2.620
Barium........	24,400	2.00–2.50	18	1.860	2.50–3.50	8	2.700
Thorium.......	24,450	1.20–2.90	277	1.803	2.90–4.20	87	2.702
Manganese.....	23,850	2.00–2.85	11	2.160	2.85–3.70	20	2.750
Nickel.........	28,300	2.00–3.40	12	1.970	3.40–4.25	2	2.760
Chromium.....	20,000	1.30–2.40	104	1.900	2.40–3.00	39	2.700
Vanadium.....	20,000	1.30–2.50	249	1.971	2.50–3.10	72	2.780
Molybdenum...	23,850	0.50–3.00	360	1.907	3.00–4.08	156	2.928
Tungsten......	23,850	0.80–2.85	292	1.863	2.85–4.80	188	2.726
			2043	$1.892 \pm 0.014_7$		827	$2.794 \pm 0.018_4$

$\frac{e}{m}$ $1.783 \pm 0.013_8 \times 10^7$ $2.633 \pm 0.017_4 \times 10^7$

It should be said that, before deciding upon the positions of the minima for these curves, they were drawn with various intervals in $\Delta\lambda/\lambda^2$, with and without the normal point ordinates described above; and the method of drawing herewith presented was selected as best representing the data. The minima were in general selected upon the original curves, before reduction to the standard field. The outer limits of the two groups are of little importance relatively, on account of the few occurrences there. A very few values of $\Delta\lambda/\lambda^2$ which were nearly one-half the value corresponding to the first maximum, or twice that value, were omitted from both groups.

The most important instance of this procedure is in the case of barium. The small distinctive group clustering around the value $\Delta\lambda/\lambda^2 = 1.90$ is not included in group I.

The appearance of a typical curve like that for chromium suggests a combination of two symmetrical overlapping curves. If this is the case, the positions of the maxima being the same for all the metals, but their relative heights different, the division of groups I and II at the minimum is not an equivalent process for all cases. For the ratio of the number of values assigned to group I but really belonging to group II, to the number assigned to group II but belonging to group I, would depend upon the relative heights of the two maxima, as would the position of the minimum itself. When the ratio of the height of the second maximum to that of the first decreases, the minimum moves out toward greater values of $\Delta\lambda/\lambda^2$, increasing group I at the expense of group II. The mean value of $\Delta\lambda/\lambda^2$ for group I is thus raised and at the same time given greater weight, while the opposite happens to group II. For nearly all of the curves shown here the second maximum is lower than the first, so that if this source of error could be removed, the two values

TABLE II

Values of $\frac{e}{m}$ by Various Observers

Färber[*]	1.710×10^7	Gmelin[**]	1.771
Lohmann[†]	1.750 1.720	Classen[‡‡]	1.776
Gehrcke and v. Baeyer[‡]	1.740	Bucherer[¶¶]	1.763
Stettenheimer[††]	1.791	Simon[***]	1.865
Weiss and Cotton[¶]	1.767	Proctor[†††]	1.859
		Mean	1.774

[*] *Annalen der Physik*, **9**, 886, 1902.

[†] Stettenheimer, Dissertation, Tübingen, 1907.

[‡] *Verhandl. der Deutschen Physikalischen Gesellschaft*, **10**. Corrected by v. Baeyer, *Physikalische Zeitschrift*, **9**, 831, 1908.

[††] Dissertation, Tübingen, 1907.

[¶] *Journal de Physique* (4), **6**, 429, 1907.

[**] *Annalen der Physik*, **28**, 1079, 1909.

[‡‡] *Physikalische Zeitschrift*, **9**, 764, 1908.

[¶¶] *Ibid.*, **9**, 760, 1908.

[***] *Annalen der Physik*, **69**, 589, 1899.

[†††] *Physical Review*, **30**, 53, 1910.

of e/m upon which the final result depends would be more accordant. It does not seem likely, however, that the final mean value would be much changed.

Table II is a collection of other determinations of e/m, the average of which is 1.774×10^7. If the values of Proctor and of Simon be omitted, however, the average falls to 1.754×10^7, but the divergence of my result from this is only a little over 1 per cent.

MOUNT WILSON SOLAR OBSERVATORY
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AN INVESTIGATION OF THE SPECTRA OF IRON AND TITANIUM UNDER MODERATE PRESSURES

By HENRY G. GALE and WALTER S. ADAMS

The results which are contained in this article are the main products of a study of the effect of a gaseous pressure of 9 atmospheres upon the arc spectrum of iron and of pressures of from 3 to 17 atmospheres upon the arc and spark spectra of titanium. The investigation was begun in the spring of 1910 and carried on during a period of three months of that year and a corresponding period of 1911. At first the end in view was to study the effects of pressure upon the spark spectrum alone, but the lack of corresponding results for the arc at moderate pressures required the extension of the investigation to include arc results as well.

Previous studies of the pressure effect have for the most part been at comparatively high pressures. Thus the recent results of Rossi[1] upon the arc spectra of titanium and vanadium are based principally upon pressures between 25 and 100 atmospheres. A part of the earlier work of Humphreys,[2] and Humphreys and Mohler,[3] dealt with pressures as low as 4 atmospheres, but all of the more recent work of Humphreys[4] has been at much higher pressures. Similarly the work of Duffield[5] upon the arc spectra of iron, gold, and silver contains some results obtained at 5, 10, and 15 atmospheres, but the great majority of his values are also for high pressures. In the case of the spark spectrum only two previous investigations are available. The first of these, by Hale and Kent,[6] deals with a small number of iron lines at pressures of from 3 to 53 atmospheres; the second, by W. B. Anderson,[7] gives the displacements of a considerable number of iron lines at 50 atmospheres.

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[1] *Proc. Roy. Soc.*, A **83**, 414, 1910.

[2] *Astrophysical Journal*, **4**, 249, 1896; **6**, 169, 1897.

[3] *Ibid.*, **3**, 114, 1895.

[4] *Ibid.*, **22**, 217, 1905; **26**, 18, 1907.

[5] *Ibid.*, **26**, 375, 1907; *Phil. Trans.*, A **208**, 111, 1908.

[6] *Astrophysical Journal*, **17**, 154, 1903.

[7] *Ibid.*, **24**, 221, 1906.

With the exception of some results by Humphreys[1] for certain lines of iron and chromium in the green and yellow parts of the spectrum all of the values given in these researches are for the more refrangible lines.

In view of these considerations it has seemed desirable to us to carry on our work at relatively low pressures and to include as large an extent of spectrum as possible. A combination of our own results with those obtained at higher pressures by other observers would give a severe test of the law of the proportionality of displacement to pressure, while the values of the displacements for lines of widely different wave-lengths would provide more satisfactory material for a discussion of the variation of displacement with wave-length than could a comparatively limited range of spectrum.

The astronomical applications of pressure results also make these considerations important. So far as our knowledge extends, the effective pressures in the reversing layer of the sun and in stellar atmospheres are moderate in amount. For example, the most recent determination of the pressure in the reversing layer of the sun by Fabry and Buisson[2] gives a value of 5 atmospheres. Accordingly pressures of the same order should be employed in the laboratory work in case a direct comparison of the character and the displacements of the lines is to be made with those in solar and stellar spectra.

The investigation has been carried on in the Pasadena laboratory of the Mount Wilson Solar Observatory and the spectrograph employed is the 9.1 m plane grating Littrow instrument already used by Mr. King and Mr. Babcock in numerous studies of the Zeeman effect. Since this spectrograph has been described in a previous publication,[3] no details are necessary in this place. The grating is a 20 cm plane grating by Michelson with 500 lines to the millimeter, and the second order has been used for all of the photographs taken in connection with this work. The linear scale given by the spectrograph is approximately 1 mm=0.95 Ångström.

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[1] *Astrophysical Journal*, **26**, 18, 1907.

[2] *Ibid.*, **31**, 97, 1910.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 23; *Astrophysical Journal*, **27**, 204, 1908.

The pressure-chamber consists of a strong brass hood with a flange at its base which is fastened by a series of iron clamps around its rim to a brass base carrying a similar flange. The two portions have been surfaced accurately and at the junction a thin lead washer provides an air-tight union. The top of the hood carries the pressure gauge and the connections for attaching the tanks of compressed gas. The connections for the electrodes are passed through the sides of the box and are very heavily insulated in order to provide for the use of high potential for the spark. The electrodes themselves consist of copper clips placed in a horizontal position, and the arc or spark passes directly between small pieces of metal held in these clips. The distance between the electrodes may be varied by means of a fiber handle on the outside of the box which turns a screw acting through a hard rubber sleeve. At moderate pressures the chamber shows very little leakage.

In the front of the brass hood is the window through which the light from the arc or spark passes to the spectrograph. Since the spectrograph itself contains a glass lens and so is not adapted for work in the extreme ultra-violet part of the spectrum, the window also is made of glass. It is about 2 cm thick and conical in shape, with its base toward the light-source in order to withstand the effect of the pressure from within. The window is mounted in the center of a round brass casting about 12 cm in diameter cut with a quarter thread. This engages with a similar thread in an opening in the pressure-chamber and the block is tightened by means of a powerful wrench, until an air-tight junction is obtained. By taking off this block it is possible to reach the electrodes without unclamping the entire box.

The light passing through the window of the pressure-chamber is focused upon the slit of the spectrograph by means of a glass lens placed midway between window and slit. It has been found possible in all of the work to obtain arc and spark gaps sufficiently wide to avoid the necessity for magnification at the slit of the spectrograph. The diameter of the lens is such that the cross-section of the cone of light at the base of the spectrograph is about six times that of the grating surface, and we have given especial care to the adjustment of the instrument in order to keep the illuminated area as nearly as possible concentric with the grating throughout all of the observations. To provide for accurate guiding during an exposure when the arc or spark shifts from one point to another upon the electrodes, we have adopted the simple expedient of placing the condensing lens upon a double-slide rack. The observer watches the image upon the slit with a small telescope and corrects for the motion of the arc or spark by a slight vertical or horizontal motion of the lens. It is evident that the effect of such motion is to displace the cone of light slightly with respect to the grating, but the margin of full illumination is so great and the motion of the lens so small that no error is to be feared from this source.

The arc used throughout this investigation was produced by a direct current of 110 volts furnished by a motor generator. A bank of lamps placed in series in the circuit provided the means of varying the amount of current passing through the arc. In general a current of from 4 to 8 amperes has been used for most of the work. By increasing or decreasing the current it is usually possible to vary the amount of reversals of the stronger comparison lines, and this has proved most useful in a part of the investigation.

The alternating current for the spark was furnished by a 5 kilowatt transformer fed by an alternating current of 220 volts. It is capable of giving a potential as great as 64,000 volts. For most of this work either 16,000 or 32,000 volts have been employed. A self-induction coil placed in the secondary circuit has been used for a part of the work for the purpose of reducing the intensities of the enhanced lines. It may be well to state at this point that we have been able to find no distinct evidence of the variation of pressure displacements with change of current, capacity, potential, or arc or spark-gaps for the range throughout which we have worked. Nor does there appear to be any difference between the results for an atmosphere of air or of carbon dioxide. The effect of a hydrogen atmosphere is discussed at a later point.

A considerable number of photographs of an arc between carbon poles was taken, and the displacements of the lines of iron, which occurred as an impurity, were found to be the same as those obtained from an arc with iron poles. Table I contains the results from arcs with iron and with carbon poles.

On all of the photographs the spectrum under pressure is placed in the center with the comparison spectrum of arc or spark at atmospheric pressure on either side, a simple occulting-bar arrangement providing for covering and uncovering the different portions of the slit. The exposure for the comparison spectrum has been divided into two parts, one-half before and one-half after the exposure for the pressure spectrum. In order to test the possible effect upon the photographs of accidental disturbances such as the vibration of the building, we have made a number of exposures upon an arc spectrum separated by considerable intervals of time, but measures of the photographs have shown no appreciable displacements since the spectrograph was definitely adjusted for this work. In general the exposure times, both for the comparison and the pressure spectrum, have been comparatively short. For the arc spectrum in the blue and violet regions they have varied from 1 to 2 minutes for the pressure spectrum to 1 to 6 minutes for the comparison spectrum on Seed "Process" plates. For the less refrangible regions the exposure times are, of course, longer, reaching in the case of the comparison spectrum a maximum of some 40 minutes in the red. The spark spectrum requires considerably more time, and in the red we have been obliged to give as much as 1½ hours to the comparison spectrum of iron.

The great amount of labor involved in the measurement and reduction of the photographs has made it impossible to determine the values of the displacements of all of the lines at all of the pressures employed. Accordingly we have adopted the plan of making as complete a study as possible of all well-measurable lines at a single pressure, and for the other pressures using a selected list sufficient in number to give a mean of high precision for purposes of comparison. The pressure adopted for the principal series was 8 atmospheres above atmospheric pressure, a value sufficiently high to give displacements of considerable amount, but not too high to prevent direct comparison with the results for solar lines. The other pressures used have been 2, 4, 6, 12, and 16 atmospheres above atmospheric pressure and a few photographs have been taken at a partial vacuum. As already stated, no appreciable difference could be detected between the displacements for an atmosphere of air or carbonic dioxide, and the latter gas has been used throughout the greater part of the investigation.

The extraordinary variety in behavior of different spectrum lines under pressure has, of course, been noted by all observers. In general the lines may be divided roughly into five broad classes:

1. Lines which are symmetrically reversed.
2. Lines which are unsymmetrically reversed.
3. Lines which remain bright and fairly narrow under pressure.
4. Lines which remain bright and symmetrical but become wide and diffuse under pressure.
5. Lines which remain bright and are widened very unsymmetrically toward the red.

The lines in the first class are those which are most readily measurable and for which the degree of precision is highest. They are much more numerous in the arc spectrum of titanium than in that of iron, and in general they are likely to be among the strongest of the lines in the spectrum. The number of lines in the second class is smaller than that in the first and the reversals as a rule are fainter. Most of the enhanced lines in the spark spectrum of titanium belong to this class.

The lines in the third and fourth classes form a majority of all of the lines measured, particularly in the less refrangible part of the spectrum where reversals are comparatively few. The lines in the third class usually are well measurable, those in the fourth less so. The distinction between these two classes is entirely arbitrary as all lines are widened somewhat under pressure.

The fifth class is of great interest. Almost all of the lines belonging to it occur in the yellow and red portions of the spectrum, and all show enormous displacements. The widening of these lines and their lack of symmetry are so great, however, that many of them are practically incapable of measurement, and for the others the degree of accuracy is extremely low. The measures when made are upon the maximum, which is always upon the violet side of the center of the line.

Most of the characteristics of the lines in the arc under pressure apply equally well to the same lines in the spark. All lines in the spark spectrum are much more diffuse, however, and the degree of accuracy of measurement is distinctly lower. This is especially true of the enhanced lines of titanium, which as a rule show very faint unsymmetrical reversals, which it is extremely difficult to measure with precision.

In the tables which follow are given the results of our measures of the displacements of the principal lines in the spectra of the iron arc and the titanium arc and spark for a total pressure of 9 atmospheres, the comparison spectrum being in each case the same source at atmospheric pressure.

The wave-length of the line according to Rowland's table is given in the first column; its type as regards reversal and symmetry, referred to one of the five classes above, in the second column; its mean displacement in the fourth column; the mean deviation of the separate determinations from the mean in the fifth column, the unit being 0.001 Ångström; and the number of plates in the sixth column. In the discussion of these displacements with relation to their variation with wave-length the lines are treated in different groups. In order to save repetition at a later point the group under which each line is treated is given in the third column. The seventh, eighth, and ninth columns in the table for titanium give the displacements of the corresponding lines in the spark spectrum, the average deviations of the separate determinations from the mean, and the number of plates measured. A few lines not given by Rowland are taken from the lists of Hasselberg[1] and Evans.[2]

In general each plate was measured four times, once in each direction, by two different observers.

Although we shall not attempt in this place to enter into any extended discussion of the characteristics of the various lines under pressure, there are a few general results evident from an inspection of these tables to which reference may be made.

1. Reversal is clearly a function of wave-length for both arc and spark. The number of reversed lines falls off rapidly toward longer wave-lengths, there being extremely few reversals in the red portion of the spectrum, for either iron or titanium. The general law was

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[1] *Astrophysical Journal* **4**, 212, 1896.

[2] *Ibid.*, **29**, 160, 1909.

TABLE I

IRON

λ	Class	Group	Δ	Mean Deviation ±	No. of Plates	λ	Class	Group	Δ	Mean Deviation ±	No. of Plates
3609.008	1	*b*	0.008	1	3	4202.198	1	*b*	0.025	9	6
3618.919	1	*b*	0.011	1	3	4204.101	3	*b*	0.017	1	2
3631.605	1	*b*	0.015	1	3	4210.494	5	*c*	0.053	2	2
3647.988	1	*b*	0.012	4	3	4216.351	3	*b*	0.015	2	2
3680.069	1	*a*	0.007	2	3	4227.606	5	*d*	0.11	10	6
3687.610	1	*b*	0.016	1	3	4233.772	5	*d*	0.09	20	7
3705.708	1	*a*	0.007	2	3	4236.112	5	*d*	0.09	20	8
3709.389	1	*b*	0.013	1	3	4250.287	5	*c*	0.070	4	2
3720.084	1	*a*	0.014	1	3	4250.945	2	*b*	0.022	4	10
3722.729	1	*a*	0.010	2	3	4260.640	2	*c*	0.051	8	8
3727.778	1	*b*	0.014	2	3	4271.934	1	*b*	0.022	3	10
3733.469	1	*a*	0.007	1	3	4282.565	1	*b*	0.021	4	7
3735.014	1	*b*	0.013	2	3	4291.630	3	*a*	0.014	0	1
3737.281	1	*a*	0.016	2	3	4294.301	2	*b*	0.029	5	6
3743.508	1	*b*	0.015	1	3	4299.410	5	*d*	0.09	20	6
3745.717	1	*a*	0.008	1	3	4308.081	1	*b*	0.021	5	7
3746.058	1	*a*	0.008	1	3	4315.262	3	*b*	0.019	3	7
3748.408	1	*a*	0.010	1	3	4325.939	1	*b*	0.020	4	7
3749.631	1	*b*	0.017	2	3	4337.216	3	*b*	0.027	2	7
3758.375	1	*b*	0.022	2	3	4352.908	3	*b*	0.017	3	7
3763.945	1	*b*	0.017	1	3	4369.941	3	*b*	0.023	3	5
3765.689	1	*b*	0.013	2	3	4376.107	3	*a*	0.018	2	7
3767.341	1	*b*	0.017	1	3	4383.720	1	*b*	0.027	4	7
3788.046	1	*b*	0.016	1	3	4404.927	1	*b*	0.021	3	7
3795.147	1	*b*	0.015	2	3	4407.871	4	*c*	0.053	2	2
3815.987	1	*b*	0.024	2	3	4408.582	4	*c*	0.058	2	2
3826.027	1	*b*	0.021	4	4	4415.293	1	*b*	0.018	5	7
3827.980	1	*b*	0.019	2	4	4422.741	3	*b*	0.018	3	2
3834.364	1	*b*	0.016	5	4	4427.482	3	*a*	0.017	3	7
3886.434	1	*a*	0.011	3	10	4430.785	4	*c*	0.048	8	4
3887.196	1	*b*	0.022	4	5	4442.510	4	*c*	0.053	9	7
3888.671	1	*b*	0.020	3	6	4443.365	3	*b*	0.019	4	6
3895.803	1	*a*	0.011	4	7	4447.892	4	*c*	0.051	9	7
3899.850	1	*a*	0.012	5	10	4454.552	3	*b*	0.023	2	2
3903.090	1	*b*	0.022	2	6	4459.301	4	*c*	0.051	8	7
3906.628	1	*a*	0.011	4	7	4461.818	3	*a*	0.015	3	7
3920.410	1	*a*	0.010	3	8	4466.727	4	*b*	0.018	4	7
3923.054	1	*a*	0.011	3	9	4476.185	4	*b*	0.021	3	7
3928.075	1	*a*	0.012	4	9	4489.911	3	*a*	0.015	2	2
3930.450	1	*a*	0.013	3	8	4494.738	4	*c*	0.053	8	6
3956.819	4	*b*	0.014	5	5	4528.798	4	*c*	0.061	4	5
3969.413	1	*b*	0.022	3	8	4531.327	3	*b*	0.029	2	4
3977.891	4	*b*	0.017	4	3	4859.928	5	*c*	0.100	4	2
3997.547	4	*b*	0.015	3	4	4871.512	5	*c*	0.080	5	4
4005.408	1	*b*	0.019	3	9	4872.332	5	*c*	0.094	5	4
4045.975	1	*b*	0.023	4	5	4878.407	5	*c*	0.087	2	2
4063.759	1	*b*	0.020	5	5	4890.948	5	*c*	0.070	8	4
4071.908	1	*b*	0.021	4	5	4891.683	5	*c*	0.052	1	4
4132.235	1	*b*	0.024	5	5	4919.174	5	*c*	0.072	3	4
4134.840	4	*b*	0.027	2	2	4920.685	5	*c*	0.082	5	4
4144.038	1	*b*	0.029	6	6	4957.480	5	*c*	0.083	5	4

TABLE I—*Continued*

λ	Class	Group	Δ	Mean Deviation ±	No. of Plates	λ	Class	Group	Δ	Mean Deviation ±	No. of Plates
4957.785	5	*c*	0.086	3	3	5659.052	5	*d*	0.15	10	2
5227.362	4	*a*	0.031	5	6	5975.575	4	*b*	0.054	7	2
5233.122	5	*d*	0.11	20	4	6027.274	4	*b*	0.062	6	3
5266.738	5	*d*	0.13	30	2	6065.709	4	*b*	0.077	5	4
5269.723	1	*a*	0.027	3	6	6136.829	4	*b*	0.082	7	4
5270.558	4	*a*	0.029	3	5	6137.915	4	*b*	0.078	3	4
5324.373	5	*d*	0.12	20	5	6157.945	4	*b*	0.041	8	3
5328.236	1	*a*	0.029	3	6	6173.553	4	*b*	0.067	5	2
5328.696	4	*a*	0.026	3	3	6191.779	4	*b*	0.086	4	4
5333.089	4	*a*	0.029	3	2	6200.527	4	*b*	0.079	10	2
5340.121	5	*d*	0.14	20	3	6213.444	4	*b*	0.072	4	3
5341.213	4	*a*	0.028	1	3	6219.494	4	*b*	0.073	2	3
5371.734	1	*a*	0.029	2	6	6230.943	4	*b*	0.070	5	4
5393.375	5	*d*	0.14	10	3	6246.535	5	*d*	0.28	10	3
5397.344	4	*a*	0.029	2	6	6252.773	4	*b*	0.077	3	6
5405.989	4	*a*	0.027	3	6	6254.456	4	*b*	0.064	4	5
5429.911	4	*a*	0.029	2	6	6256.572	4	*b*	0.089	5	4
5434.740	4	*a*	0.027	2	6	6265.348	4	*b*	0.070	4	5
5447.130	4	*a*	0.031	3	6	6298.007	4	*b*	0.068	2	1
5455.834	4	*a*	0.029	1	5	6301.718	5	*d*	0.25	30	2
5476.500	4	*a*	0.029	2	3	6318.239	4	*b*	0.080	4	2
5476.778	5	*d*	0.11	10	2	6335.554	4	*b*	0.074	3	2
5497.735	3	*a*	0.030	2	3	6337.048	5	*d*	0.26	10	2
5501.683	3	*a*	0.030	3	3	6393.820	4	*b*	0.072	7	2
5507.000	3	*a*	0.031	4	3	6400.217	5	*d*	0.24	10	2
5535.644	4	*a*	0.034	4	3	6411.865	5	*d*	0.23	10	2
5569.848	5	*d*	0.14	10	5	6421.570	4	*b*	0.068	2	2
5573.075	5	*d*	0.14	10	5	6431.066	4	*b*	0.068	4	2
5576.320	5	*d*	0.16	10	2	6495.213	4	*b*	0.065	4	2
5586.991	5	*d*	0.12	2	2	6546.479	4	*b*	0.073	3	2
5603.186	5	*d*	0.15	10	2	6593.161	4	*b*	0.076	6	2
5615.877	5	*d*	0.13	20	2	6594.121	4	*b*	0.070	2	2
5624.769	5	*d*	0.16	10	2	6678.235	4	*b*	0.086	1	3
5638.488	5	*d*	0.15	10	2						

stated by Hale in 1902[1] for the spark under pressure, but Duffield's[2] observations upon the iron arc between λ 4000 and λ 4500 did not appear to indicate the same effect for this source. Apparently the discrepancy is due to the comparatively limited region of spectrum investigated by Duffield.

2. The number of unsymmetrical bright lines increases toward longer wave-lengths. This is true particularly of the high-temperature lines of iron, the low-temperature lines (those relatively

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[1] *Astrophysical Journal*, **15**, 227, 1902.

[2] *Phil. Trans.*, A **208**, 111, 1908.

TABLE II

TITANIUM

λ	CLASS	GROUP	ARC			SPARK			
			Δ	Mean Deviation ±	No. of Plates	Δ	Mean Deviation ±	No. of Plates	
3729.952	1	*a*	0.009	1	3	.....	..	..	
3741.205	1	..	0.011	1	3	.....	..	..	
3753.003	1	*a*	0.014	4	3	.....	..	..	
3753.732	1	*a*	0.006	2	2	.....	..	..	
3759.447	1	..	0.011	4	4	.....	..	..	Enhanced line
3761.464	1	..	0.008	1	4	.....	..	..	Enhanced line
3771.798	1	*a*	0.007	3	3	.....	..	..	
3898.645	3	*a*	0.014	3	4	0.019	1	3	
3900.681	3	..	0.034	12	5	0.041	5	4	Enhanced line
3901.114	2	*a*	0.010	4	5	0.019	4	2	
3904.926	1	*a*	0.019	4	7	0.023	3	4	
3913.609	3	..	0.036	4	6	0.037	3	4	Enhanced line
3914.477	1	*a*	0.006	2	6	0.017	2	4	
3921.563	1	*a*	0.005	2	6	0.013	4	4	
3924.673	1	*a*	0.010	2	6	0.020	4	4	
3926.465	4	..	0.048	5	5	0.042	2	2	
3930.022	1	*a*	0.008	3	6	0.018	3	4	
3947.918	1	*a*	0.004	2	6	0.014	4	4	
3948.818	1	*a*	0.013	2	7	0.021	6	4	
3956.476	1	*a*	0.010	2	6	0.021	4	4	
3958.355	1	*a*	0.015	3	7	0.021	1	3	
3962.995	1	*a*	0.010	4	6	0.021	1	4	
3964.416	1	*a*	0.010	3	6	0.022	7	4	
3981.917	1	*a*	0.016	4	8	0.022	3	3	
3982.630	1	*a*	0.006	2	6	0.020	2	4	
3989.912	1	*a*	0.016	3	9	0.016	7	3	
3998.790	1	*a*	0.016	5	9	0.015	3	3	
4009.079	1	*a*	0.008	2	5	0.019	1	4	
4009.807	2	*a*	0.009	2	5	0.020	2	4	
4021.893	4	..	0.051	2	3	.....	..	..	
4024.726	1	*a*	0.008	1	4	0.021	1	4	
4028.497	3	..	0.018	2	2	.....	..	..	Enhanced line
4060.415	1	*a*	0.015	2	4	0.025	4	4	
4065.239	1	*a*	0.011	2	4	0.023	2	4	
4078.631	1	*a*	0.005	1	4	0.017	2	4	
4082.589	1	*a*	0.019	4	4	0.025	3	4	
4099.327	4	*a*	0.028	3	4	0.025	2	2	
4112.869	1	*a*	0.014	3	4	0.015	1	4	
4151.129	4	*a*	0.034	7	4	0.031	2	3	
4159.805	4	*a*	0.035	4	4	0.025	1	2	
4163.818	4	..	0.041	2	4	.....	..	..	Enhanced line
4164.27	4	*a*	0.031	9	4	.....	..	..	
4166.45	4	*a*	0.030	3	3	.....	..	..	
4169.46	4	*a*	0.034	1	3	.....	..	..	
4171.213	4	*a*	0.035	3	4	0.044	0	2	
4172.066	4	..	0.042	2	3	.....	..	..	Enhanced line
4174.61	4	*a*	0.035	7	3	.....	..	..	
4183.45	4	*a*	0.040	1	3	.....	..	..	
4186.280	1	*a*	0.016	3	5	0.030	1	4	

TABLE II—*Continued*

λ	Class	Group	Arc			Spark			
			Δ	Mean Deviation ±	No. of Plates	Δ	Mean Deviation ±	No. of Plates	
4188.84	4	a	0.044	2	4	.....	..	..	
4200.946	4	a	0.039	4	3	.....	..	..	
4203.620	4	a	0.038	2	4	0.030	1	2	
4224.792	4	..	0.064	2	3	.....	..	..	
4227.822	4	..	0.073	1	3	.....	..	..	
4238.00	4	a	0.014	1	4	.....	..	..	
4263.290	4	a	0.026	2	2	.....	..	..	
4265.832	4	a	0.037	1	2	.....	..	..	
4272.701	3	a	0.016	2	4	.....	..	..	
4276.587	4	a	0.030	3	4	.....	..	..	
4278.390	4	a	0.043	3	4	.....	..	..	
4281.530	4	a	0.014	3	4	.....	..	..	
4282.860	4	a	0.027	2	4	.....	..	..	
4285.164	4	a	0.036	3	4	.....	..	..	
4286.168	1	a	0.021	2	4	.....	..	..	
4287.566	1	a	0.024	2	4	.....	..	..	
4288.310	3	a	0.019	1	4	.....	..	..	
4289.237	1	a	0.025	3	4	.....	..	..	
4290.080	3	a	0.033	1	4	.....	..	..	
4290.377	3	..	0.046	2	5	0.048	9	6	Enhanced line
4291.114	1	a	0.022	2	5	0.016	2	6	
4294.204	3	..	0.029	1	5	0.039	6	6	Enhanced line
4295.914	1	a	0.022	2	5	0.015	3	5	
4298.828	1	a	0.025	2	4	0.019	2	6	
4299.410	1	a	0.023	3	4	0.034	4	6	
4299.803	1	a	0.023	2	4	0.024	3	6	
4300.211	3	..	0.029	4	4	0.051	4	6	Enhanced line
4300.732	1	a	0.021	2	4	0.018	3	6	
4301.158	1	a	0.024	1	4	0.025	2	6	
4302.085	3	..	0.033	2	2	.....	..	..	Enhanced line
4306.078	1	a	0.024	2	4	0.027	4	6	
4308.64	3	a	0.019	6	3	.....	..	..	
4313.034	3	..	0.047	4	3	.....	..	..	Enhanced line
4314.479	3	a	0.018	3	3	.....	..	..	
4314.964	1	..	0.032	4	3	.....	..	..	
4326.520	3	a	0.029	2	4	0.025	3	6	
4338.084	3	..	0.017	3	4	0.040	8	6	Enhanced line
4346.26	3	a	0.006	2	3	.....	..	..	
4360.644	3	a	0.042	4	3	.....	..	..	
4394.093	4	a	0.015	3	3	.....	..	..	
4395.201	3	..	0.025	2	3	.....	..	..	Enhanced line
4399.935	3	..	.....	..	..	.....	..	..	
4417.450	3	a	0.027	4	4	0.033	3	6	
4421.928	4	..	0.038	8	3	.....	..	..	Enhanced line
4422.985	4	a	0.028	4	3	.....	..	..	
4426.201	4	a	0.026	5	3	.....	..	..	
4427.266	1	a	0.017	3	7	0.026	1	7	
4434.168	4	a	0.035	4	3	.....	..	..	
4440.515	4	a	0.029	5	4	0.027	4	6	
4443.976	4	..	0.021	2	4	0.040	4	6	Enhanced line
4449.313	1	a	0.029	4	8	0.033	3	9	

TABLE II—*Continued*

λ	Class	Group	Arc			Spark			
			Δ	Mean Deviation ±	No. of Plates	Δ	Mean Deviation ±	No. of Plates	
4451.087	1	*a*	0.029	2	9	0.037	3	3	
4453.486	1	*a*	0.040	4	10	0.045	3	9	
4453.876	1	*a*	0.026	5	5	0.042	2	2	
4455.485	1	*a*	0.041	2	9	0.048	2	3	
4457.600	1	*a*	0.039	3	10	0.044	4	9	
4465.975	1	*a*	0.025	2	10	0.033	4	9	
4468.663	4	..	0.046	4	6	0.059	7	8	Enhanced line
4471.408	1	*a*	0.024	4	10	0.029	4	9	
4475.026	4	..	0.074	4	5	.....	..	..	
4479.879	4	*a*	0.027	2	5	0.025	1	2	
4480.752	3	*a*	0.027	4	5	0.032	4	2	
4481.438	1	*a*	0.023	2	10	0.031	3	9	
4488.493	..	..	.....	..	..	0.054	7	2	Enhanced line
4489.262	1	*a*	0.029	5	6	0.033	4	8	
4501.445	4	..	0.046	4	6	0.063	6	8	Enhanced line
4512.906	1	*a*	0.029	2	10	0.039	4	9	
4518.198	1	*a*	0.029	2	10	0.039	3	9	
4518.866	3	*a*	0.025	5	5	0.029	1	2	
4522.974	1	*a*	0.031	3	10	0.040	4	9	
4527.490	1	*a*	0.029	3	10	0.041	4	9	
4533.419	1	*a*	0.031	2	10	0.036	3	9	
4534.139	3	..	0.044	5	6	0.063	3	7	Enhanced line
4534.953	1	*a*	0.034	3	10	0.036	5	9	
4535.741	1	*a*	0.029	3	9	0.031	3	3	
4536.094	1	*a*	0.023	2	4	0.036	2	2	
4536.222	1	*a*	0.031	1	2	.....	..	..	
4544.864	1	*a*	0.031	2	10	0.035	2	9	
4548.938	1	*a*	0.031	2	10	0.039	6	9	
4549.808	4	..	0.048	2	6	0.062	8	8	Enhanced line
4552.632	1	*a*	0.029	3	10	0.041	3	9	
4555.662	1	*a*	0.029	2	8	0.041	3	9	
4562.814	3	*a*	0.008	1	5	0.026	5	2	
4563.939	4	..	0.034	4	6	0.053	6	7	Enhanced line
4572.156	4	..	0.051	5	6	0.065	4	8	Enhanced line
4590.126	..	..	.....	..	..	0.052	5	2	Enhanced line
4617.452	1	*a*	0.029	2	5	0.038	1	2	
4623.279	1	*a*	0.027	3	5	0.040	4	2	
4629.521	1	*a*	0.037	4	5	0.042	4	2	
4638.050	4	*a*	0.043	3	3	.....	..	..	
4645.368	1	*a*	0.039	6	3	0.043	2	2	
4650.193	4	*a*	0.037	4	3	0.040	4	2	
4656.644	1	*a*	0.017	2	3	0.027	2	2	
4667.768	1	*a*	0.020	4	3	0.023	1	2	
4675.294	4	*a*	0.030	1	3	0.051	2	2	
4682.088	1	*a*	0.018	2	3	0.018	1	2	
4691.523	1	*a*	0.038	2	3	.....	..	..	
4698.946	2	*a*	0.037	2	3	0.036	2	2	
4710.368	1	*a*	0.041	4	3	0.046	7	2	
4722.797	4	*a*	0.036	4	3	.....	..	..	
4723.359	4	*a*	0.040	2	3	.....	..	..	
4742.979	1	*a*	0.037	4	3	0.040	2	2	

TABLE II—*Continued*

λ	Class	Group	Arc			Spark			
			Δ	Mean Deviation ±	No. of Plates	Δ	Mean Deviation ±	No. of Plates	
4758.308	1	*a*	0.027	7	5	0.030	0	2	
4759.463	1	*a*	0.031	4	5	0.036	2	2	
4766.48	3	*a*	0.036	2	3	.....	..	..	
4778.441	4	*a*	0.049	4	3	.....	..	..	
4781.91	3	*a*	0.034	1	3	.....	..	..	
4799.984	4	*a*	0.038	6	3	0.044	4	2	
4805.285	3	..	0.048	2	3	.....	..	..	Enhanced line
4805.606	4	*a*	0.074	4	6	.....	..	..	
4820.593	1	*a*	0.033	6	9	0.041	1	3	
4836.313	4	*a*	0.051	7	7	.....	..	..	
4841.074	1	*a*	0.007	2	10	0.018	2	3	
4848.605	4	*a*	0.029	1	3	.....	..	..	
4856.203	1	*a*	0.029	2	6	.....	..	..	
4868.451	1	*a*	0.026	4	4	.....	..	..	
4870.323	1	*a*	0.029	4	5	.....	..	..	
4885.264	1	*a*	0.026	4	7	.....	..	..	
4900.095	1	*a*	0.018	4	4	.....	..	..	
4913.803	1	*a*	0.022	6	4	.....	..	..	
4915.414	3	*a*	0.021	4	4	.....	..	..	
4919.99	4	*a*	0.029	4	4	.....	..	..	
4921.963	4	*a*	0.029	2	4	.....	..	..	
4928.511	4	*a*	0.032	4	4	.....	..	..	
4975.530	4	*a*	0.028	1	4	.....	..	..	
4981.912	1	*a*	0.025	5	7	.....	..	..	
4991.247	1	*a*	0.029	1	7	.....	..	..	
4997.283	3	*a*	0.013	1	4	.....	..	..	
4999.689	1	*a*	0.028	2	7	.....	..	..	
5007.398	1	*a*	0.027	2	7	.....	..	..	
5009.829	3	*a*	0.017	1	4	.....	..	..	
5014.369	2	*a*	0.021	6	4	.....	..	..	
5016.340	1	*a*	0.027	4	4	.....	..	..	
5020.208	1	*a*	0.029	5	4	.....	..	..	
5023.052	1	*a*	0.028	2	5	.....	..	..	
5025.027	1	*a*	0.027	2	4	.....	..	..	
5036.089	1	*a*	0.045	4	4	.....	..	..	
5036.645	1	*a*	0.042	3	4	.....	..	..	
5038.579	1	*a*	0.048	5	4	.....	..	..	
5040.138	1	*a*	0.005	2	4	.....	..	..	
5040.787	3	*a*	0.034	2	4	.....	..	..	
5043.761	3	*a*	0.032	4	4	.....	..	..	
5045.582	3	*a*	0.029	3	4	.....	..	..	
5053.056	4	*a*	0.035	4	4	.....	..	..	
5062.285	4	*a*	0.034	5	4	.....	..	..	
5064.836	1	*a*	0.012	1	4	.....	..	..	
5066.12	4	..	0.069	5	3	.....	..	..	
5071.666	4	*a*	0.080	5	4	.....	..	..	
5087.239	4	*a*	0.032	5	4	.....	..	..	
5109.601	3	*a*	0.032	2	2	.....	..	..	
5113.617	4	*a*	0.032	8	4	0.026	7	2	
5120.592	4	*a*	0.007	1	3	.....	..	..	
5145.636	4	*a*	0.029	7	4	.....	..	..	

TABLE II—*Continued*

λ	Class	Group	Arc			Spark			
			Δ	Mean Deviation ±	No. of Plates	Δ	Mean Deviation ±	No. of Plates	
5147.652	4	*a*	0.017	1	4	0.022	2	2	
5152.361	4	*a*	0.018	2	4	0.024	2	2	
5173.917	1	*a*	0.023	2	2	0.021	1	2	
5193.139	1	*a*	0.019	4	7	0.022	3	5	
5210.555	1	*a*	0.015	3	6	0.016	2	4	
5212.503	4	*a*	0.047	2	3	.....	..	..	
5219.875	3	*a*	0.025	4	3	0.037	2	2	
5238.742	3	*a*	0.048	2	3	0.041	2	3	
5246.30	4	*a*	0.018	2	3	.....	..	..	
5246.733	4	*a*	0.033	2	2	.....	..	..	
5251.085	4	*a*	0.027	6	3	.....	..	..	
5252.276	3	*a*	0.023	2	3	0.031	2	3	
5255.973	5	..	0.29	50	3	.....	..	..	
5260.142	5	..	0.33	30	2	.....	..	..	
5263.669	5	..	0.26	110	3	.....	..	..	
5266.141	5	..	0.17	20	2	.....	..	..	
5282.576	3	*a*	0.028	5	3	0.042	1	3	
5283.613	5	..	0.15	20	3	.....	..	..	
5284.601	3	*a*	0.035	9	3	.....	..	..	
5289.02	4	*a*	0.042	5	2	.....	..	..	
5295.955	4	*a*	0.027	3	3	0.048	2	3	
5297.407	5	..	0.13	5	3	.....	..	..	
5298.672	5	..	0.088	5	3	.....	..	..	
5300.152	3	*a*	0.030	6	3	.....	..	..	
5313.422	3	*a*	0.035	1	2	.....	..	..	Probably *Ti*
5338.517	3	*a*	0.043	5	2	.....	..	..	
5341.77	4	*a*	0.068	4	2	.....	..	..	
5351.261	5	..	0.27	20	3	.....	..	..	
5366.827	3	*a*	0.032	1	3	0.043	2	3	
5369.782	4	*a*	0.027	2	3	0.030	3	3	
5389.371	3	*a*	0.029	3	3	.....	..	..	
5390.203	4	*a*	0.029	2	3	0.052	2	3	
5396.778	3	*a*	0.018	2	3	0.053	..	3	
5404.25	4	*a*	0.057	6	3	.....	..	..	
5409.81	4	*a*	0.015	1	2	0.042	1	3	
5419.42	4	*a*	0.047	6	3	.....	..	..	Probably *Ti*
5426.474	3	*a*	0.029	9	3	0.044	1	3	
5429.349	4	*a*	0.044	1	3	.....	..	..	
5436.938	3	*a*	0.046	11	3	0.043	2	3	
5438.507	3	*a*	0.053	6	2	.....	..	..	
5446.797	3	*a*	0.027	7	3	.....	..	..	
5453.860	4	*a*	0.051	4	3	0.046	3	3	
5460.721	3	*a*	0.019	5	3	0.035	1	3	
5471.414	4	*a*	0.037	2	3	0.045	1	3	
5472.90	4	*a*	0.030	1	3	.....	..	..	
5474.436	3	*a*	0.029	2	3	.....	..	..	
5482.078	3	*a*	0.028	3	3	.....	..	..	
5490.367	4	*a*	0.038	5	3	.....	..	..	
5504.117	4	*a*	0.074	4	3	.....	..	..	
5512.013	3	*a*	0.021	1	3	.....	..	..	
5512.741	1	*a*	0.044	6	3	.....	..	..	

TABLE II—*Continued*

λ	Class	Group	Arc			Spark			
			Δ	Mean Deviation ±	No. of Plates	Δ	Mean Deviation ±	No. of Plates	
5514.563	1	*a*	0.048	2	2	.....	..	..	
5514.753	1	*a*	0.043	2	2	.....	..	..	
5565.700	4	*a*	0.049	6	8	.....	..	..	
5597.90	3	..	0.000	0	5	.....	..	..	Fluting line
5644.365	4	*a*	0.033	1	5	.....	..	..	
5648.796	5	..	0.29	40	3	.....	..	..	
5662.374	5	..	0.23	3	3	.....	..	..	
5675.647	5	..	0.25	20	3	.....	..	..	
5689.694	5	..	0.25	10	3	.....	..	..	
5702.876	5	..	0.25	20	3	.....	..	..	
5708.46	5	..	0.24	10	4	.....	..	..	
5712.07	5	..	0.25	20	4	.....	..	..	
5715.308	4	*a*	0.048	3	5	.....	..	..	
5727.271	3	*a*	0.058	4	3	.....	..	..	
5739.698	4	*a*	0.042	2	5	.....	..	..	
5740.195	3	*a*	0.029	2	5	.....	..	..	
5781.130	3	*a*	0.046	5	5	.....	..	..	
5823.910	3	*a*	0.032	1	4	.....	..	..	
5866.675	1	*a*	0.034	2	5	.....	..	..	
5880.55	3	*a*	0.029	3	5	.....	..	..	
5899.518	4	*a*	0.034	1	5	.....	..	..	
5903.555	3	*a*	0.025	2	5	.....	..	..	
5918.773	3	*a*	0.022	4	6	.....	..	..	
5922.334	4	*a*	0.048	4	3	.....	..	..	
5938.035	3	*a*	0.038	2	3	.....	..	..	
5941.985	4	*a*	0.050	4	3	.....	..	..	
5953.386	4	*a*	0.020	3	3	.....	..	..	
5966.055	4	*a*	0.036	4	3	.....	..	..	
5978.768	4	*a*	0.018	3	3	.....	..	..	
5996.11	3	*a*	0.028	1	3	.....	..	..	
5999.920	3	*a*	0.050	1	3	.....	..	..	
6064.853	3	*a*	0.024	4	3	.....	..	..	
6085.490	4	*a*	0.020	4	3	.....	..	..	
6091.395	4	*a*	0.048	2	3	.....	..	..	
6093.00	5	..	0.14	2	2	.....	..	..	
6098.92	5	..	0.33	20	3	.....	..	..	
6121.24	5	..	0.16	2	2	.....	..	..	
6126.435	4	*a*	0.018	4	3	.....	..	..	
6146.48	5	..	0.15	5	2	.....	..	..	
6150.02	3	*a*	0.049	4	3	.....	..	..	
6186.65	3	..	0.000	0	3	.....	..	..	Fluting line
6258.322	1	*a*	0.071	7	6	0.065	8	3	
6258.927	1	*a*	0.066	8	5	0.061	1	3	
6261.316	1	*a*	0.070	10	5	0.065	6	3	
6303.985	4	*a*	0.048	3	2	0.076	4	3	
6336.329	3	*a*	0.029	7	2	0.042	3	3	
6366.564	3	*a*	0.032	6	2	0.038	2	3	
6497.92	3	*a*	0.056	5	2	0.061	5	3	
6508.37	3	*a*	0.057	2	2	0.049	6	3	
6546.479	4	*a*	0.049	6	2	0.061	1	3	
6554.470	4	*a*	0.034	6	2	0.060	14	3	

TABLE II—*Continued*

λ	Class	Group	Arc			Spark		
			Δ	Mean Deviation ±	No. of Plates	Δ	Mean Deviation ±	No. of Plates
6556.308	4	*a*	0.049	0	2	0.059	2	3
6599.353	3	*a*	0.035	15	2	0.052	1	3
6719.90	4	*a*	0.058	3	2	.....	..	..
6861.770	4	*a*	0.084	2	2	.....	..	..

strengthened at low temperatures) being symmetrical and, though broad, fairly well defined as a rule.

3. Except in the ultra-violet the enhanced lines of titanium are always bright in the arc under a pressure of 9 atmospheres. In the titanium spark at the same pressure they are usually faintly reversed. This agrees with Duffield's hypothesis that conditions in the electric spark are more favorable to the production of reversals than they are in the arc.

4. The number of reversed lines at a pressure of 9 atmospheres is somewhat less than that found by Duffield[1] for pressures of 20 to 25 atmospheres. This agrees with the conclusion of Humphreys that in the case of iron, for moderate pressures at least, the number of reversals increases with the pressure.

Some additional characteristics of certain of the lines will be referred to in the course of the discussion of the displacements.

Since our work upon the iron spectrum has been limited to the arc, and all of the photographs have been taken at a pressure of 9 atmospheres, while the results for titanium include both arc and spark, and for some of the lines a variety of pressures as well, we shall discuss the displacements for the two elements separately.

IRON

In the following table we have compared our results with the most recent values obtained by Humphreys and by Duffield[2] for such lines as are common to all three sets of observers. To reduce to a value of 9 atmospheres total pressure, Duffield's values for

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[1] *Phil. Trans.*, A **208**, 111, 1908.

[2] *Jahrbuch der Radioaktivität und Elektronik*, **5**, 324, 1908.

11 atmospheres are reduced by one-fifth, while Humphreys' values for 42 atmospheres are divided by the quantity 5.1. Series B in Duffield's investigation has been used, as this is considered preferable by the author.

λ	Humphreys	Duffield	Gale and Adams
4132.235	0.020	0.021	0.024
4144.038	.023	.021	.029
4202.198	.014	.017	.025
4233.772	.047	.144	.090
4250.945	.017	.018	.022
4260.640	.048	.051	.051
4271.934	.016	.017	.022
4282.565	.009	.018	.021
4294.301	.017	.019	.029
4308.081	.018	.019	.021
4315.262	.007	.013	.019
4325.939	.019	.026	.020
4337.216	.018	.034	.027
4352.908	.010	.020	.017
4369.941	.011	.026	.023
4376.107	.008	.017	.018
4404.927	.022	.043	.021
4415.293	.017	.033	.018
4422.741	.013	.022	.018
4427.482	.011	.018	.017
4430.785	.037	.057	.048
4442.510	.037	.057	.053
4443.365	.012	.022	.019
4447.892	.035	.062	.051
4454.552	.016	.018	.023
4459.301	.031	.063	.051
4461.818	.012	.018	.015
4466.727	.011	.021	.018
4476.185	.014	.021	.021
4494.738	.040	.058	.053
4531.327	0.015	0.026	0.029

If we omit the line λ 4233.772, which is unsymmetrical and extremely difficult of measurement, a comparison of the remaining 30 lines gives the following mean values:

Humphreys	0.019
Duffield	0.029
Gale and Adams	0.027

The agreement of our results with those of Duffield is close, but the average value found for the observations of Humphreys is rather surprisingly small. This may be due in part to the fact that the linear relationship between displacement and pressure fails to hold at high pressures, although this seems improbable in view of the very close accordance found by other observers for several elements and shown by our own measures upon the titanium spectrum. A few of these lines measured by Humphreys in a previous investigation at lower pressures give distinctly larger values for the displacements, and these agree closely with those obtained by Duffield and ourselves.

In any discussion of the effect of pressure upon the lines of the spectrum there is a natural tendency to institute a comparison with the other two causes which are known to affect different lines of a spectrum differently. The first of these is variation of temperature; the second is the presence of a magnetic field.

The lines of iron which are strengthened relatively at low temperatures and which are usually referred to as "flame" lines are well known.[1] The most prominent of these lines for which we have determined the pressure displacements are the following:

λ	Δ	λ	Δ
3680.069	0.007	4427.482	0.017
3705.708	.007	4461.818	.015
3720.084	.014	4489.911	.015
3722.600	.010	5227.362	.031
3733.469	.007	5269.723	.027
3737.281	.016	5328.236	.029
3745.717	.008	5333.089	.029
3746.058	.008	5341.213	.028
3748.408	.010	5371.734	.029
3886.434	.011	5397.344	.029
3895.803	.011	5405.989	.027
3899.850	.012	5429.911	.029
3906.628	.011	5434.740	.027
3920.410	.010	5447.130	.031
3923.054	.011	5455.834	.029
3928.075	.012	5476.778	.029
3930.450	.013	5497.735	.030
4291.630	.014	5501.685	.030
4376.107	0.018	5507.000	0.031

With the exception of the two lines λ 4291.630 and λ 4489.911, which are faint, all of these lines are suitable for measurement, being fairly sharp under pressure, and the precision of the results is high, especially for the more refrangible lines. Except in the violet region there are no reversed lines among them.

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[1] De Watteville, *Phil. Trans.*, A **204**, 139, 1904; Adams, *Contributions from the Mount Wilson Solar Observatory*, No. 40; *Astrophysical Journal*, **30**, 86, 1909.

It is apparent at a glance that the displacements given by these lines are decidedly smaller than those of the other lines in the same region. The average displacement of the 17 flame lines in the ultra-violet region is about 0.010 Ångström, while the average for 27 other lines in the same region is 0.015. In the green region the difference is even more striking, although here it is not possible to compare the flame lines directly with the other lines in the same region owing to the fact that the latter appear to belong to a totally distinct group as regards displacements, giving values about four times as great as the flame lines. We can, however, compute a value for this region from the value in the blue region, assuming the law of variation according to the cube of the wave-length which seems to hold closely for these lines. In this way we obtain 0.044 as against 0.029 for the flame lines. An interesting characteristic of the flame lines is the close agreement of the displacements of the different lines in the same part of the spectrum. This fact taken in connection with their behavior at reduced temperatures makes it very probable that they form members of a single group. An examination of the results obtained by King[1] for the electric-furnace spectra under pressure shows that the flame lines give distinctly lower displacements than the other lines in this source as well. It is worthy of note that in an investigation of the displacement of the spectrum lines at the sun's limb[2] it was found that the flame lines in general gave smaller values than the other lines of the same element.

A study of the relationship between displacements under pressure and separations in a magnetic field has been made by King[3] for a large number of iron lines and a considerable number of titanium and chromium lines. For the purpose of comparing the displacements and separations he has formed the quotients of all the lines for which the data are available, and from a comparison of these quotients has concluded that no direct relationship exists between the two quantities, although for the average of large groups of lines the effects are in the same direction.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 53; *Astrophysical Journal*, **34**, 37, 1911.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 43; *Astrophysical Journal*, **31**, 30, 1910.

[3] *Contributions from the Mount Wilson Solar Observatory*, No. 46; *Astrophysical Journal*, **31**, 433, 1910.

It is hardly possible in this place to repeat the calculations with the use of the values of the displacements given in this investigation. A few results, however, which can readily be confirmed are as follows:

1. The use of the pressure displacements given here reduces greatly a considerable number of the largest differences found by King. As examples we may refer to λ 3920.410, λ 3923.054, λ 3928.075, λ 3977.891, λ 4315.262, and λ 4376.107, all of which are brought into much closer agreement with the other lines.

2. A majority of the serious discordances between pressure displacements and magnetic separations are in the cases of lines which are found to be complex in the magnetic field. Apart from the uncertainty of measurement of the separations of many of these lines, it is improbable on the basis of any of the theories of the Zeeman effect that there would be a direct relationship between separations and pressure displacements for such lines except perhaps for those of exactly the same type. We should expect rather that these lines would be greatly widened under pressure. It is interesting to note in this connection that nearly all of the strong flame lines in the yellow portion of the spectrum are complex in the magnetic field, while many of the other lines are triplets. The former lines show some of the most serious discrepancies between separation and displacement that are found in the entire list. Similarly in the violet part of the spectrum we may refer to the complex lines λ 4191.595 and λ 4233.722, which show large differences.

3. Since the pressure displacements for iron vary as the cube of the wave-length and the magnetic separations as the square, it is necessary in comparing the results to multiply the separations by the ratio of wave-lengths. This is found to bring the results in the less refrangible region of the spectrum into much closer agreement with those in the violet.

4. It seems probable from the fact that the lines of iron appear to divide themselves into groups, both as regards pressure displace-

ments and magnetic separations, that the ratios of the two quantities may by no means be the same for different groups, although constant within any given group for the same types of lines.

5. The significance of the agreement of very large and very small displacements and separations for certain lines seems to us of great importance. Of the former type we may mention the triplets λ 4210.494, λ 4407.871, λ 4430.785, and λ 4878.407. In the red we may refer to the triplet λ 6302.709, which is not measurable under pressure but has an immense displacement. The evidence from the behavior of such a group of lines as that between λ 4430 and λ 4461, for which displacements and separations unmistakably rise and fall together, is especially important.

6. The number of very marked discrepancies between size of displacement and separation among the triplets is not large, but a few of them are very important. A single most striking case is λ 6173.553 which gives an average pressure displacement but an exceedingly wide separation. It is a wide triplet in sun-spots. Another case in which the discordance is not so great is λ 4071.908.

7. Three lines which show no measurable separation in a magnetic field have been measured under pressure. Two of them, λ 3746.058 and λ 5434.740, give small displacements under pressure, while the third line, λ 3767.341, gives an average value. All three are rather narrow under pressure.

8. Attention should be called to the extreme sensitiveness of these comparisons to errors of observation. To illustrate: if we assume a magnetic separation of 0.350 Ångström for a given line and a pressure displacement of 0.020 Ångström, which is not far from an average value for the violet, we obtain the quotient 17.5. For the very best lines under pressure it is difficult to obtain probable errors of less than ±0.002, which would produce a variation in the quotient of from 16 to 19. For many lines the probable error is several times this amount. Furthermore, our experience with titanium at different pressures indicates that the probable error increases almost in proportion to the pressure, so that the use of high pressures brings little gain on account of the deterioration of the lines. On the side of the magnetic separations errors of measurement also influence the comparisons, so that a very con-

siderable range in the results is to be expected from these sources. The type of separation also is very often uncertain, as is shown by the numerous changes in classification made by the same observer when different analyzing apparatus is used.

In view of these results it seems to us that the balance of evidence is somewhat in favor of a direct relationship between pressure displacements and separations in the magnetic field for lines which are of the same type. For lines of complex type and for lines which under pressure become extremely unsymmetrical the values are discordant, a result which is not surprising.

VARIATION OF DISPLACEMENT WITH WAVE-LENGTH

As soon as the measures of the displacements for all the iron lines were completed we plotted the results upon a large scale, using wave-lengths as abscissas and displacements as ordinates. A similar chart is shown in Fig. 1. The chart at once shows that certain groups of lines for which the average displacements differ widely apparently belong together. Furthermore, a comparison of the displacements of the flame lines with those of the other lines indicates clearly that such lines are to be considered as a separate group. In this way four groups have been found, and the lines included in each group are indicated in Table I by the letters *a*, *b*, *c*, and *d*. Group *a* includes all of the flame lines and two or three additional lines in the yellow portion of the spectrum, which may be flame lines but for which observations are lacking. Group *b* is a large one and includes all lines of small displacements which are not included in group *a*. It may well be complex in nature but in the absence of criteria for separating it into smaller groups we are obliged to consider it as a unit. Group *c* consists of lines showing much larger displacements than those of group *b*. It contains two fairly distinct clusters of lines, one in the violet and one in the blue green. The lines are all bright under pressure and especially in the green region unsymmetrical and difficult of measurement. Group *d* is made up of a very few lines in the violet, a fair-sized group in the greenish yellow, and a small number in the red, all of which show immense displacements. The lines are bright and widened enormously to the red, the wings extending sometimes from 5 to 10

Ångström units. The precision of measurement upon these lines necessarily is very low, in some cases the determination amounting to little more than an estimate of the maximum within the broad band.

The average values of the displacements and of the corresponding wave-lengths for the lines forming these groups provide us the material for a discussion of the variation of displacement with wave-length. In the following table the results are collected for the four groups. The second column gives the mean of the wave-lengths of the lines for which the mean displacement is formed. The third column contains the mean displacements expressed in Ångström units. The fourth column gives the number of lines for each portion of the group. It is evident from a simple inspection of the

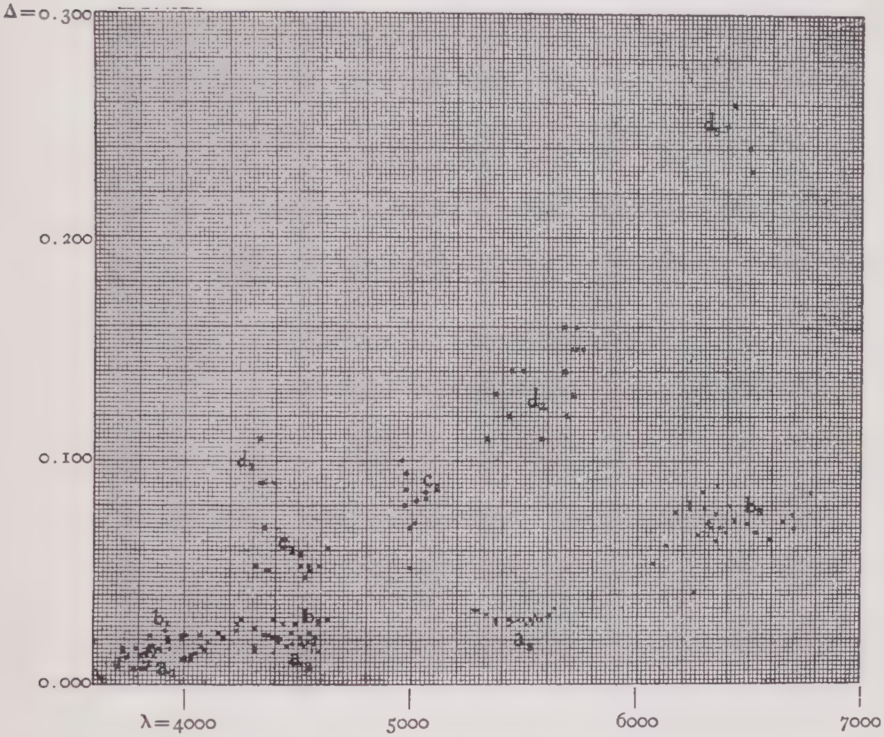

FIG. 1.—Displacement of lines of the iron arc at 8 atmospheres pressure.

results that the increase of displacement toward longer wave-lengths is much more than would be given by a law based on the first power of the wave-length. In the last two columns of the table are given the residuals for two hypotheses: first, that the displacement varies as the square of the wave-length; second, that it varies as the cube of the wave-length.[1] The reductions have been made by least squares, with weights assigned according to the number of lines. The fourth group is of course of very low weight compared with the others.

Group	Mean λ	Mean Δ	No. Lines	Residuals (Obs.—Comp.)	
				$\Delta=\left(\frac{\lambda}{\lambda_0}\right)^2 k$	$\Delta=\left(\frac{\lambda}{\lambda_0}\right)^3 k$
a...........	3813	0.0105	17	−0.0032	+0.0002
	4409	.0158	5	−0.0025	−0.0001
	5398	.0292	19	+0.0017	−0.0001
b...........	3791	.0164	27	−0.0072	+0.0007
	4287	.0219	29	−0.0083	−0.0008
	6292	.0719	27	+0.0069	+0.0001
c...........	4395	.0547	11	−0.0058	−0.0020
	4902	.0803	10	+0.0051	+0.0016
d...........	4249	.09	4	−0.01	+0.02
	5498	.14	15	−0.02	−0.01
	6339	0.25	5	+0.04	+0.01

These results are also shown graphically in Fig. 2. The points correspond to the observed, and the curves to the computed values, assuming the law of the cube of the wave-length.

It is clear from the results that the displacements for all of the groups of lines are represented with a surprisingly high degree of accuracy by a law which involves the third power of the wave-length, and in view of the great range of wave-length covered by the observations this may probably with safety be assumed to be true of the entire iron spectrum. In some recent work by Rossi upon the arc spectrum of vanadium,[2] he concludes from his observa-

[1] Strictly speaking the means of the second and third powers of the individual wave-lengths should be used instead of the second and third powers of the means of the wave-lengths, but the difference is negligible for the purposes of this comparison.

[2] *Astrophysical Journal*, **34**, 21, 1911.

tions that "the displacement seems to be roughly proportional to the square or a higher power of the wave-length," and Duffield in his investigation of the iron spectrum found that the linear relationship would not hold. Similarly Duffield in his discussion of the effect of pressure upon the arc spectra of silver and gold writes:[1]

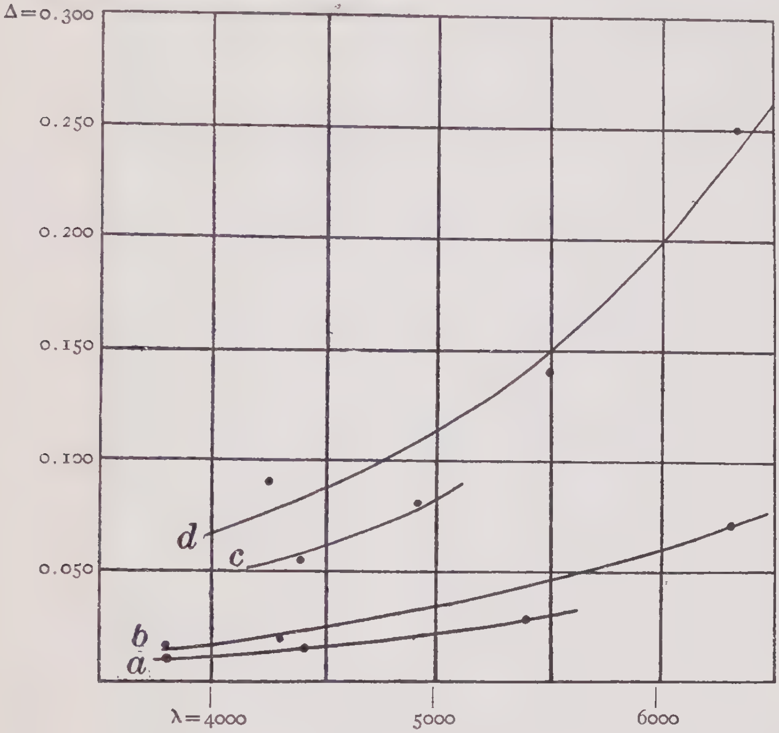

FIG. 2.—Mean displacement and mean wave-length of iron groups. Curves represent computed, points observed, values.

> It seems at least certain that the displacement varies with a higher power of the wave-length than the first upon which it was previously believed to depend. The results of the present investigation favor a dependence upon the third power of the wave-length, and this agrees with some theoretical deductions made by Dr. O. W. Richardson.[2]

From the results of his investigation of the iron spectrum Duffield concluded that there are three groups of lines for which the displacements are approximately in the ratio of 1:2:4. A comparison with his results shows that so far as the same lines have been measured these groups are identical with our groups *b*, *c*, and *d*, except for the fact that we have included the flame lines in a separate group. In addition, the line λ 4260.640 which Duffield places in group 3 is placed by us in group *b*. It is a very unsymmetrically reversed line and subject to great variations in appearance under pressure. If we compare the violet portions of these groups, reducing to wave-length λ 4287, we obtain the ratios:

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[1] *Phil. Trans.*, A **211**, 66, 1911.

[2] *Phil. Mag.*, **14**, 557, 1907.

b	*c*	*d*
1	2.3	4.5

Similarly Duffield has for his groups:

I	II	III
1	2.0	4.5

The agreement between the two sets of results is close and in view of the accuracy of the results the departure from the whole numbers seems to be sufficiently great to make the integer relationship improbable. If we include the group of flame lines we obtain the ratio 0.67 between groups *b* and *a;* or, if we reduce all values to group *a* we find the relationship:

a	*b*	*c*	*d*
1	1.5	3.4	6.6

If the first two groups are united we have the ratios

1	2.5	4.9

It seems to us therefore improbable that the displacements of the different groups of iron lines bear ratios to one another which are proportional to small integers.

TITANIUM

Two previous investigations of the arc spectrum of titanium under pressure are available. The first of these, by Humphreys,[1] was carried on at pressures between 42 and 101 atmospheres, and the second, by Rossi,[2] at pressures between 16 and 101 atmospheres. Unfortunately very few lines are common to all three series of observations. A comparison with the results of Humphreys shows that our values are larger by about the same amount as in the case of iron. The average of the lines agrees well with that of Rossi, although there are some large individual discrepancies.

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[1] *Astrophysical Journal*, **26**, 18, 1907.

[2] *Proc. Roy. Soc.*, A **83**, 414, 1910.

One of the features which stands out most prominently in these results is the behavior of the enhanced lines. A large majority of them show displacements decidedly larger than those of the great proportion of arc lines in the vicinity, in some parts of the spectrum the average difference amounting to as much as 50 per cent. The effect, however, is not true of all enhanced lines, such lines, for example, as λ 4338.084 and λ 4443.976 showing small values as compared with neighboring arc lines. Nearly all of the enhanced lines present in the arc spectrum are bright at a pressure of 9 atmospheres, and being rather broad and diffuse are difficult of measurement. We have for this reason given especial attention to them, particularly in the region λ 4300 to λ 4600, and few of the values are based upon the measurement of less than four plates. The exceptional behavior of most of these lines is fully confirmed by the spark results, and is of marked interest in view of their importance in solar and stellar spectroscopy.

An inspection of the results given in Table II shows that the intermixture of the groups in the spectrum of titanium, if such exist, must be most complicated, and the simple expedient of plotting the displacements graphically, which proved so useful in separating the groups of lines in the iron spectrum, has been of little value. In the violet part of the spectrum nearly all of the lines as far as λ 4080 are reversed and show small displacements. At this point, however, begins a series of unreversed lines extending to λ 4285, which show relatively large displacements. Beyond λ 4290 both reversed and unreversed lines occur and the average displacement is less than in the region λ 4080–λ 4290. In the green, yellow, and red portions of the spectrum the number of reversed lines falls off steadily but the displacements are found to range between very small and very large values, although showing a marked increase on the average. There is probably little doubt that the collection of lines showing displacements of some 0.2 Ångström in the green and yellow parts of the spectrum form parts of a group similar to group *d* in the iron spectrum. The violet members of this group may perhaps be λ 4318 and λ 4321, which have displacements of about 0.1 Ångström. These lines are all unreversed and immensely widened toward the red, and very similar in appearance to the iron lines of group *d*.

A comparison of the titanium lines of group *a* with those which are affected in sun-spots shows that the lines which are most strengthened in spots as a rule show small displacements under pressure, although the agreement is by no means perfect. The fact that the number of low-temperature lines increases very rapidly in the less refrangible parts of the spectrum may account, perhaps, for the lower average for the displacements of the titanium lines in these regions.

In view of the impossibility of separating the groups in the titanium spectrum it is perhaps not surprising that a general comparison of our pressure displacements with the separations in a magnetic field gives little evidence of any direct relationship between these quantities. As in the case of iron, the use of these displacements instead of those of Humphreys reduces in a marked degree the number of large discordances for lines which are simple triplets in the magnetic field. Such lines, however, as λ 4841.074, λ 5040.138, and λ 5120.592, which show very small pressure displacements but average separations, must necessarily form part of a separate group and a much larger number of groups than in the case of iron must be assumed in order to account for the wide variations observed. The question must be considered an open one.

The relationship between displacement and wave-length in the case of titanium clearly is complicated by the presence of the different groups of lines. A rather surprising result is given if we form simple means of the displacements for definite regions of the spectrum. Omitting the enhanced lines and some lines with very large displacements already referred to, the remainder (indicated by *a* in Table II) give the average values on the following page.

In the last two columns are given the residuals, assuming: first, that the displacement varies as the square of the wave-length; second, that it varies as the third power of the wave-length. The results show clearly that the law of the square of the wave-length satisfies the observations the more closely. In the iron spectrum, on the other hand, the law was found to be the third power of the wave-length. As already indicated, the relatively large value of the average displacement in the violet is due to a considerable extent to the group of unreversed lines of large shifts between λ 4080 and λ 4285. If these were omitted, however, and only reversed lines considered throughout the entire spectrum, the difficulty would remain that the reversed lines in the region λ 4400 to λ 4600 give a value of the displacement quite as large on the average as do the reversed lines in the region λ 4800 to λ 5200. Accordingly it seems impossible without separating the lines in a very arbitrary way to obtain a series of average displacements which will harmonize with a law based upon the third power of the wave-length. It is sufficient to state that for the general averages of large numbers of lines taken throughout the spectrum the law of the square of the wave-length seems to hold closely, and to leave further discussion to a time when it is possible to distinguish groups in the titanium spectrum.

REGION	MEAN λ	MEAN Δ	NO. LINES	RESIDUALS (OBS.—COMP.)	
				$\Delta=\left(\frac{\lambda}{\lambda_0}\right)^2 k$	$\Delta=\left(\frac{\lambda}{\lambda_0}\right)^3 k$
3700–4700...	4288	0.0250	115	+0.0016	+0.0064
4700–5700...	5142	0.0344	100	+0.0008	+0.0023
5700–6900...	6127	0.0439	38	−0.0038	−0.0102

It may be of interest in this connection to call attention to some other results which suggest the possibility that the law of variation of displacement with wave-length may differ between titanium and iron. At the sun's limb the lines of nearly all the elements are shifted slightly toward the red relative to their positions in the spectrum of the center of the sun,[1] a result due probably to the greater influence of the lower strata of gas in the production of the lines in the limb spectrum. A study of the displacements of a large number of lines of different elements by Adams[2] shows that in the case of iron the change of displacement with wave-length is not

[1] Halm, *Astronomische Nachrichten*, **173**, 273, 1907.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 43; *Astrophysical Journal*, **31**, 30, 1910.

far from proportional to the square of the wave-length, while in the case of titanium it is much less, being more nearly proportional to the first power. In other words, if two groups of iron and titanium lines had the same average displacement in one part of the spectrum λ_0, in any other part λ the average displacements would bear the relationship

$$\Delta_{Fe}=\left(\frac{\lambda}{\lambda_0}\right)\Delta_{Ti}\,.$$

This is the same result as that which we have found for iron and titanium under pressure. Conditions in the sun are, of course, very complicated, and the displacement of each line depends upon its level, the amount of scattering and absorption of light in different portions of the spectrum, the thickness of the absorbing vapor, and many other factors as well. For these reasons we might expect that the law of variation of displacement with wave-length would differ from that found in laboratory spectra. Unless we assume a radically different level for iron and titanium in the solar atmosphere, however, we should expect the two elements to bear the same relationship to one another in the sun as that which they bear in the laboratory, and this appears to be the case.

Another result which may have a bearing upon the question of a difference in the laws of variation of displacement with wave-length for different elements is contained in a few measurements we have made upon some series lines in the spectrum of calcium at a pressure of 9 atmospheres (total). The second subordinate series of calcium contains a triplet in the violet beginning at λ 3949 and a triplet in the red at λ 6102. The red lines are fairly well measurable, but the violet lines are extremely poor in quality. We have, however, succeeded in obtaining a few measures upon two of them. The results follow:

λ	Δ	No. Plates
3957.177	0.081	3
3973.864	.085	3
6102.937	.139	2
6122.434	.136	2
6162.390	0.137	2

The close agreement of the separate lines is largely accidental, as their quality is not such as to warrant it. Averaging the two sets of lines we find:

λ	Δ	Obs.—Comp.
3965	0.083	−0.003
6129	0.137	+0.004

It is clear that the relationship between displacement and wave-length for these results is very nearly a linear one. The last column gives the residuals on such a hypothesis. Since these are series lines there can be no doubt of their connection with one another, and although the accuracy of measurement is low, it is hardly probable that the results can be in error sufficiently to admit of a law containing the second power of the wave-length, much less the third.

Although it is not possible to consider differences in the law of change of displacement with wave-length for different elements as established by these results, there is perhaps sufficient evidence to warrant a reference to the chemical relationship of the three elements. Calcium, titanium, and iron appear in the second, fourth, and eighth groups of the Mendeléjeff table, with atomic weights of 40, 48, and 56, and atomic volumes of 25, 13, and 7, respectively. It is perhaps conceivable that the law which connects pressure displacement with wave-length may be different for the different groups of the Mendeléjeff table.

The principal question remaining for consideration in these results is that of a possible difference between the displacements of arc and spark lines at the same pressure. The quality of the spark lines under pressure unfortunately is as a rule by no means equal to that of the corresponding arc lines, the reversals being much wider and more diffuse and the unreversed lines often less symmetrical. An inspection of the tables shows a marked tendency toward higher values for the spark displacements. Probably the most accurate results may be obtained from a comparison of a list of 20 lines, none of which is enhanced, between λ 4427 and λ 4555, employed in an investigation of the variation of displacement with amount of pressure and given in Table III. These lines have been measured upon an exceptionally large number of spark photographs so that the results obtained should be reasonably comparable in accuracy with the arc values. Taking the means of the displacements of these 20 lines we find the values:

$$\Delta_{\text{spark}}=0.037,\quad \Delta_{\text{arc}}=0.030;\quad \text{or } \Delta_{\text{spark}}-\Delta_{\text{arc}}=0.007 \text{ Ångström.}$$

Very nearly the same value is given by a comparison of the lines throughout the entire spectrum. It seems hardly probable that a difference of this magnitude can be due to uncertainty of measurement, and the fact that arc and spark photographs were taken under exactly the same conditions, sometimes alternating with one another, reduces the probability of instrumental source of error. Since the reversals of the spark lines are broader than those of the arc it is possible that the larger displacements in the spark are due to an average widening of the reversals toward the red more than toward the violet, and as the amount of this effect would no doubt be peculiar to each line it might well account for the large variations between separate lines. The reversals in most cases, however, appear symmetrical upon the photographs.

In the case of the enhanced lines the differences between arc and spark displacements are even more marked. *The average difference for all of the enhanced lines which occur in both lists is* 0.014 *Ångström*, or about twice that found for the other lines. The values are

$$\Delta_{\text{spark}}=0.051;\quad \Delta_{\text{arc}}=0.037.$$

The enhanced lines in the spark spectrum are exceedingly difficult of measurement, but there probably can be little question of the existence of a difference of considerable size. The percentage of increase of the spark values over those of the arc also is greater than for the other lines.

The important question whether the relationship between displacement and amount of pressure is strictly linear has been considered by all who have carried on pressure investigations. Humphreys, Duffield, and Rossi have all shown that over a wide range of pressures, for the most part above 15 atmospheres, the displacements are directly proportional to pressure within the accuracy of the observations, although Duffield found some contradictory results between 15 and 25 atmospheres. In order to make an accurate test of the law at low pressures we have taken a special series of photographs of the titanium arc in the region λ 4300–λ 4600 at pressures ranging from 2 atmospheres to 16 atmospheres above atmospheric pressure. A few photographs in a partial vacuum have been obtained as well. We have selected a list of 20 lines, all of which are reversed and well adapted for measurement on these photographs, and have used the averages of the displacements of these 20 lines at the various pressures for purposes of comparison. The results for each line together with the mean deviations are given in Table III.

TABLE III

λ	2 Atmos. 6 Plates		4 Atmos. 4 Plates		6 Atmos. 4 Plates		8 Atmos. 10 Plates		12 Atmos. 4 Plates		16 Atmos. 4 Plates	
	Δ	Mean Dev.	Δ	Mean Dev.	Δ	Mean Dev.	Δ	Mean Dev.	Δ	Mean Dev.	Δ	Mean Dev.
4427.266	4	1	9	2	15	1	17	3	30	2	41	2
4449.313	8	2	15	1	24	2	29	4	49	1	69	2
4451.087	8	1	16	3	25	3	28	2	48	3	73	3
4453.486	12	1	23	2	33	1	40	4	62	6	87	7
4455.485	12	1	24	3	34	3	41	2	64	3	92	6
4457.600	10	1	23	3	33	2	39	3	63	1	86	3
4465.975	8	2	15	1	21	2	25	2	42	1	51	5
4471.408	7	1	12	1	19	2	23	3	44	1	53	6
4481.438	6	1	13	1	19	2	23	2	43	2	59	3
4512.906	9	1	15	2	25	2	30	2	50	3	68	3
4518.198	8	1	15	2	25	1	30	2	45	2	68	5
4522.974	9	1	16	3	25	1	31	3	52	2	71	6
4527.490	9	1	17	2	26	1	32	4	48	1	71	2
4533.419	8	1	17	2	24	1	31	2	49	4	66	1
4534.953	12	3	13	1	25	1	34	3	49	1	70	2
4535.741	8	1	15	1	24	2	29	3	51	1	66	3
4544.864	9	1	16	4	26	1	31	2	50	3	68	2
4548.938	8	1	17	2	25	3	31	2	51	3	70	5
4552.632	8	1	17	2	24	2	30	3	50	1	70	6
4555.662	10	1	17	3	28	2	31	2	55	3	75	6
Mean..	8.6	1	16.2	2	25.0	2	30.3	3	49.8	2	68.7	4

If we assume the linear relationship and reduce the mean values by a least-squares solution we obtain the following residuals:

	Obs.—Comp.	Δ per Atmos.
2 atmos..........	+0.0005	0.0043
4 atmos..........	−0.0003	.0040
6 atmos..........	+0.0003	.0042
8 atmos..........	−0.0026	.0038
12 atmos..........	+0.0004	.0042
16 atmos..........	+0.0028	0.0043

The largest deviation from the linear law, accordingly, at any of these pressures is found to be only 0.0028 Ångström. The displacement per atmosphere is given in the last column of the table. The average of these values is 0.0041 Ångström. Similarly for the average displacement between 15 and 100 atmospheres for 16 of the same lines Rossi finds 0.0045. The close agreement of these results makes it almost certain that the linear law of the variation of displacement with pressure holds perfectly between atmospheric pressure and 101 atmospheres. The results are shown graphically in Fig. 3.

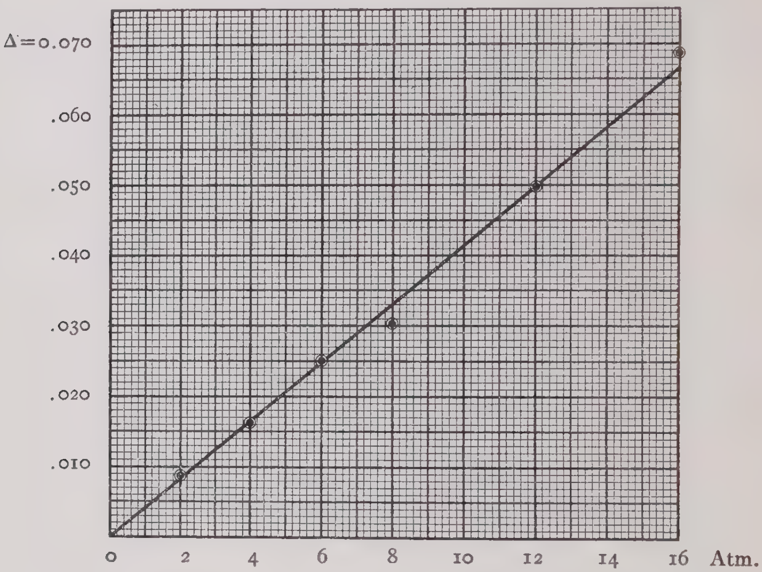


Fig. 3.—Mean displacement of 20 selected titanium lines at different pressures.

In the course of the investigation a number of photographs were made of the titanium arc in an atmosphere of illuminating gas. The arc under such conditions burns very poorly, and it is necessary to employ a very short gap and secure the exposure from a series of intermittent flashes rather than a continuous flame as in air or carbon dioxide. The photographs were all made at a pressure of 4 atmospheres. It is well known that an atmosphere of hydrogen has the effect of strengthening the enhanced lines at atmospheric pressure and the same is found to be true at a pressure of 4 atmospheres. We have measured on these photographs most of the arc lines in the selected list of 20 lines and also all well-measurable enhanced lines in the same region. The appearance of the lines does not differ greatly from that in an atmosphere of carbon dioxide except for the greater relative strength of the enhanced lines. The arc lines measured are all reversed; the enhanced lines unreversed. The results are shown in Table IV, compared with the corresponding values for the same pressure in an atmosphere of carbon dioxide. The displacements are in thousandths of an Ångström.

TABLE IV

λ	4 Atmos. H	No. Plates	4 Atmos. CO_2	No. Plates	Difference $\Delta_H-\Delta_{CO_2}$	
4427.266	11	5	9	4	+ 2	
4443.976	9	6	7	5	+ 2	Enhanced line
4449.313	15	2	15	4	0	
4451.087	13	2	16	4	− 3	
4453.486	23	2	24	4	− 1	
4455.485	22	5	24	4	− 2	
4457.600	24	5	23	4	+ 1	
4465.975	15	5	14	4	+ 1	
4468.663	31	6	26	5	+ 5	Enhanced line
4471.408	10	2	11	4	− 1	
4481.438	10	2	13	4	− 3	
4501.445	34	6	27	5	+ 7	Enhanced line
4512.906	14	5	15	4	− 1	
4518.198	17	2	15	4	+ 2	
4522.974	14	2	16	4	− 2	
4527.490	17	5	17	4	0	
4534.139	24	6	20	5	+ 4	Enhanced line
4544.864	17	5	16	4	+ 1	
4548.938	14	2	17	4	− 3	
4549.808	41	6	31	5	+10	Enhanced line
4555.662	15	4	17	4	− 2	
4563.939	29	6	22	5	+ 7	Enhanced line
4572.156	41	5	33	5	+ 8	Enhanced line

The interesting result is brought out by these measures that while the 16 arc lines in the list give practically identical values in hydrogen and carbon dioxide, the enhanced lines show distinctly larger values in hydrogen. The average values for $\Delta_H-\Delta_{CO_2}$ are:

16 arc lines..................	−0.0007
7 enhanced lines............	+0.0061

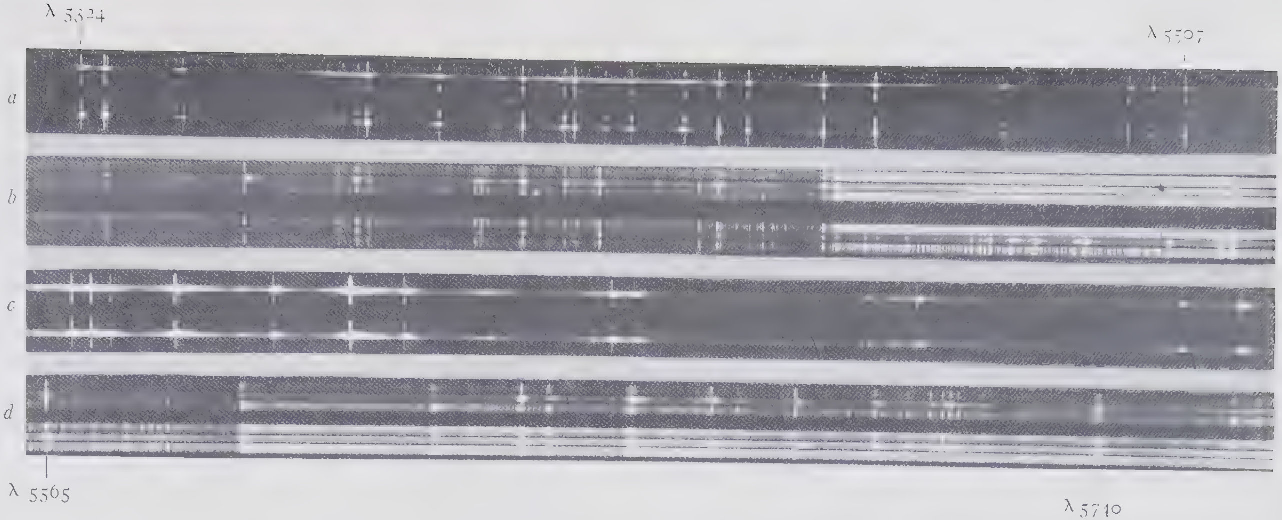
Moreover, the increase of displacement in hydrogen for an enhanced line seems to be a direct function of the normal displacement of the line, amounting to about 25 per cent at 4 atmospheres. Thus the line λ 4443.976 which is displaced only 0.007 in CO_2 is displaced 0.009 in H, while λ 4501.445 which is displaced 0.027 in CO_2 is displaced 0.034 in H, the same ratio holding for both. In view of the quality of the lines and the accuracy of the measures it seems to us that this result is almost certainly geniune and that the nature of the surrounding gas exerts an influence upon the displacements of the enhanced lines. It appears probable, therefore, that a change from a carbon dioxide to a hydrogen (illuminating gas) atmosphere affects not only the intensities but the displacements of the enhanced lines in the same way as does a change from arc to spark.

We have already referred to some of the more important applications of the results of this investigation to solar spectroscopy. The fact that the enhanced lines show materially larger displacements both at the sun's limb and under pressure than do the other lines strengthens greatly the view that pressure is the effective agent in producing the solar displacements. As was pointed out previously, evidence in the same direction is afforded by the two facts that both in the arc under pressure and at the sun's limb the low-temperature lines give small displacements, and that both in arc and sun the ratio of the laws of change of displacement with wave-length for iron and titanium is the same. We have referred briefly in an earlier communication[1] to the possible bearing upon the character of the spectrum of the solar chromosphere of the fact that at moderate pressures the enhanced lines remain bright while a majority of the other lines are reversed. A result which probably has an application in the same direction but especially to the spectrum of the upper chromosphere and of prominences is furnished by our photographs of the titanium arc at reduced pressure. These show a marked increase of relative intensity for the enhanced lines as compared with that which they have at atmospheric pressure.[2] At the very low pressures of the upper portions of the solar atmosphere this fact may well account for the prominence of the enhanced

[1] *Science*, **32**, 881, 1910.

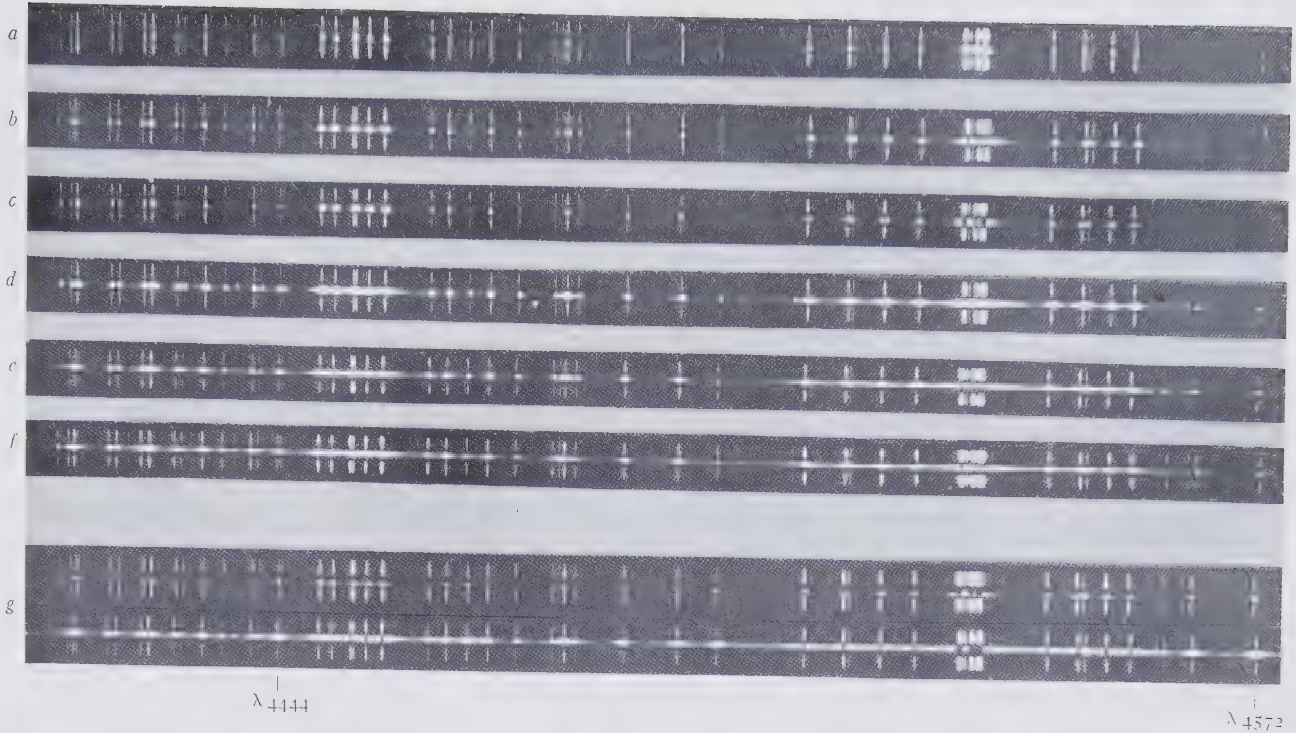
[2] A similar result has been found by Barnes for *Al*, *Mg*, and *Cu*, *Astrophysical Journal*, **34**, 159, 1911.

PLATE IX



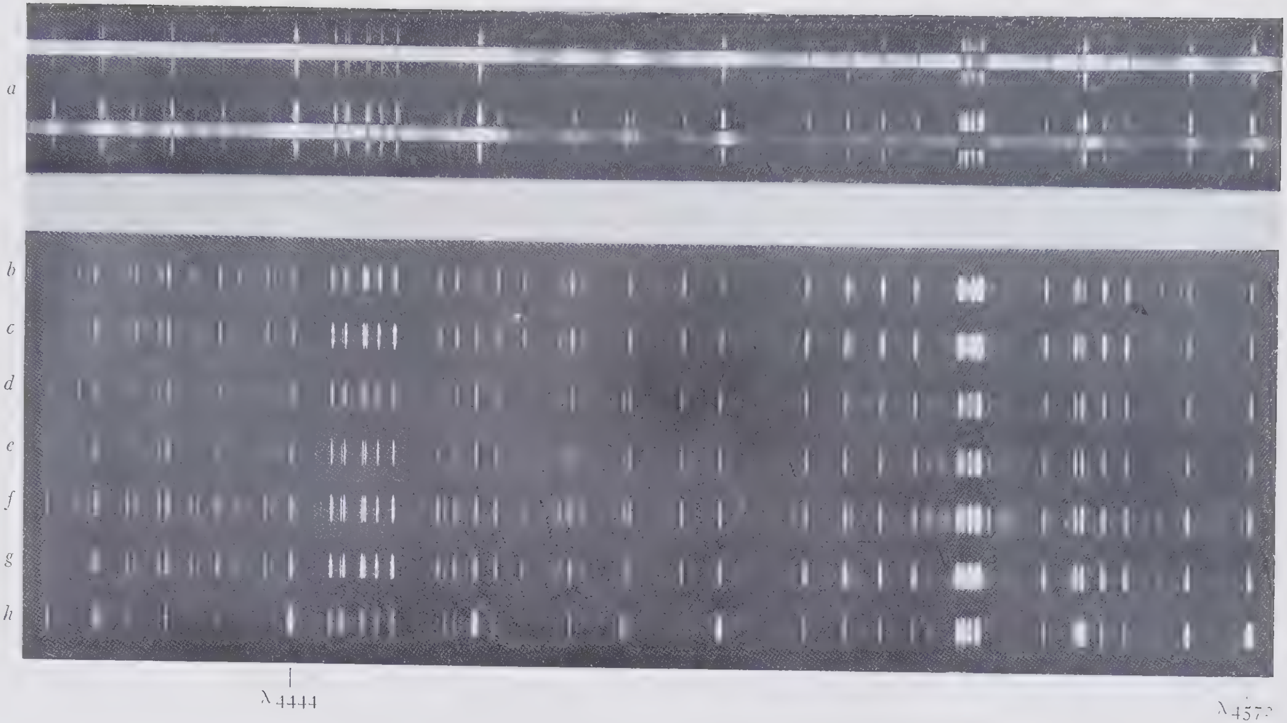
a and *c*, iron; *b* and *d*, titanium; all at 9 atmospheres; comparison, 1 atmosphere
a and *b* same region; *c* and *d* same region

PLATE X



Ti arc at different pressures; comparison at 1 atmosphere
a, b, c, d, e, f, at 2, 4, 6, 8, 12, and 16 atmospheres, respectively, above atmospheric pressure
g, *Ti* arc in atmosphere of illuminating gas, at 4 atmospheres above atmospheric pressure

PLATE XI



a, *Ti* spark, 9 atmospheres; comparison, spark at 1 atmosphere
b and *c*, arc 1 atmosphere
d and *e*, arc 10 cm
f, arc 1.5 cm
g, spark with self-induction and capacity
h, spark with capacity, but no self-induction

lines in the flash spectrum. The change of intensities of the enhanced lines at reduced pressure is well shown in Plate XI.

SUMMARY

An investigation of the arc spectrum of iron at a pressure of 9 atmospheres and of the arc and spark spectra of titanium at pressures of from a partial vacuum to 17 atmospheres over a range of wave-length from λ 3600 to λ 6800 furnishes the following results:

1. Reversal is a function of wave-length, being most frequent in the more refrangible part of the spectrum and becoming less so toward longer wave-lengths.

2. With reduction of pressure below one atmosphere the enhanced lines in the spectrum of titanium become relatively stronger.

3. The low-temperature lines of iron appear to form a distinct group and have small displacements under pressure.

4. The other lines of iron may be divided into three groups for which the displacements bear the approximate ratios 1 : 2.3 : 4.5. If the flame lines are taken as a separate group the ratios are 1 : 1.5 : 3.4 : 6.6.

5. There appears to be some evidence in favor of a direct relationship between pressure displacement and magnetic separation for iron when lines of the same group and of the same type of separation are considered. In the case of titanium, for which it has not been possible to distinguish well-marked groups of lines, no evidence of a connection with magnetic separation is found.

6. The values of the average displacement for the four iron groups at different wave-lengths are well represented by a law of variation of displacement with the third power of the wave-length. If we form simple means of the displacements of the titanium lines for considerable portions of the spectrum the values are well represented by a law of variation with the second power of the wave-length. The difference from iron may be due to the intermixture of various groups in the titanium spectrum. Measures of some calcium lines belonging to the second subordinate series indicate a variation of displacement according to the first power of the wave-length. The measures, however, are of low weight.

7. The displacements of the titanium arc lines are found to be accurately proportional to pressure for a range of from 2 to 16 atmospheres above atmospheric pressure.

8. The enhanced lines as a rule show much larger displacements under pressure than do the other lines in the titanium arc spectrum and are almost always unreversed. The amount of displacement, however, depends upon each individual line and a few enhanced lines give very small values.

9. In an atmosphere of hydrogen (illuminating gas) the displacements of the enhanced lines are appreciably larger than in an atmosphere of air or carbon dioxide at the same pressure. The other lines show the same displacements.

10. The displacements of the lines in the titanium spark appear to be larger on the average than in the arc, the largest differences being for the enhanced lines.

In the difficult work involved in the measurement of the photographs we have so far as possible followed the plan of having each plate measured by two observers. We are greatly indebted to Miss Lasby for her skilful treatment of the photographs and her active interest throughout the progress of the entire investigation.

MOUNT WILSON SOLAR OBSERVATORY
November 1911

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THE THREE-PRISM STELLAR SPECTROGRAPH OF THE MOUNT WILSON SOLAR OBSERVATORY

By WALTER S. ADAMS

The original design of the 60-inch reflector provided for the use of three stellar spectrographs in connection with the three principal mirror combinations. The first of these to be completed was the powerful spectrograph of 5.5 m focal length used with the coudé combination of telescope mirrors at the equivalent focus of 45.7 m. This instrument was employed for the investigation of the spectra of some of the brighter stars under high dispersion.[1] In the following year a small low-dispersion spectrograph was constructed for use at the primary focus of the large mirror. On account of the presence of the Newtonian plane mirror it was necessary to mount this spectrograph on the side of the tube of the telescope and to introduce an auxiliary reflection between the slit and the collimating lens. The instrument proved extremely efficient for qualitative work upon the spectra of faint stars, and the radial velocity results obtained with it were so promising as to warrant the construction of an instrument of similar type mounted directly in the axis of the telescope. In this way the loss of light at two reflecting surfaces is avoided and much greater mechanical stability is insured. This spectrograph is now nearing completion in the Observatory instrument shops.

Intermediate between these two spectrographs, one of very high and the other of low dispersion, is the three-prism spectrograph mounted at the lower end of the telescope tube and employed with the Cassegrain combination of mirrors. At this point the equivalent focal length of the telescope is 24.4 m, or the ratio of aperture to focal length is 1 to 16. This is much the same ratio as that of most of the large refracting telescopes used for spectrographic work, and accordingly the dimensions of the optical system in the spectrograph are similar to those of some of the larger stellar spectrographs employed in radial velocity determinations. The instrument was built by William Gaertner & Co. of Chicago in accordance with designs provided by the observatory, and has been in regular use on Mount Wilson during the past year.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 50; *Astrophysica Journal*, **33**, 64–71, 1911.

The very massive character of the telescope mounting and the proximity of the spectrograph to the center of rotation of the telescope made the consideration of its weight of less importance than is usually the case. Accordingly the main frame of the instrument consists of a single heavily ribbed iron casting. The base of the casting is rectangular in shape and about 84×61 cm in size. It is accurately surfaced and is attached directly to a planed flange upon the frame of the telescope by means of a number of strong studs. The slit of the spectrograph is behind the face of the casting and so is well protected from possible injury during the process of changing of instruments. The opening in the telescope frame through which the light passes from the diagonal plane mirror is about 33 cm in diameter, being made sufficiently large to provide for direct photography at this point. The corresponding aperture in the spectrograph casting opposite the slit is about 15 cm square.

At right angles to this base and forming a part of the same casting is the large plate which constitutes the frame of the spectrograph. It is about three-quarters of an inch in thickness and is planed over a large portion of its surface. Fastened directly to this plate are the prisms and the tubes carrying the collimating and camera lenses. The plate is about 140 cm long and tapers slightly from its base toward the prism box.

The focal length of the collimating lens was determined by two considerations: first, the size of the prisms available for use; and second, in a less degree, by the fact that a very long instrument would prevent observations of the region of the sky near the pole on account of striking the floor of the dome. The difficulty of securing optical glass of a quality suitable for prisms of considerable size is very great at the present time, as is fully recognized by most spectroscopists. Fortunately, in the case of this spectrograph, prisms of good quality were known to be available. At the time at which the five-foot spectroheliograph was designed four prisms 210 mm high and with faces 125 mm wide were ordered from Jena. Three of these proved to be of excellent quality. They are of glass No. O. 102, with an angle of 63° 29′, which provides for a deviation of 180° at $H\gamma$ when three prisms are employed. Since only two prisms are required for the work of the spectroheliograph the third prism became available for the stellar spectrograph. Accordingly it was cut in our optical shop into three prisms, each 67 mm high and with faces the same, of course, as those of the original prism; that is, 125 mm in width. A prism with faces of this size would utilize a beam 59 mm in width at minimum deviation for $H\gamma$. In view of these considerations a diameter of 64 mm (2.5 inches) was fixed upon for the aperture of the collimating lens, which with a ratio of 1 to 16 gives a focal length of 102 cm (40 inches). When more than one prism is employed there is an appreciable loss of light for wave-lengths other than that at minimum deviation on account of the spread of the beam, but as the spectrograph was designed largely for work with one prism it seemed desirable to retain the large aperture. The collimating lens is a cemented triplet corrected for the $H\gamma$ region, made by the J. A. Brashear Co., and has proved very satisfactory in use.

Two camera lenses have been employed with the spectrograph. The longer one of these is an uncemented triplet by Brashear of 88 mm aperture and 102 cm focal length. The other is a Cooke lens of the "Astro-photographic" type with an aperture of 102 mm and a focal length of 46 cm. Both lenses give excellent definition, and the latter, on account of the transparency and the thinness of its components, has proved exceptionally efficient photographically. For all work with a single prism the longer camera has been used, while with two prisms the shorter camera has usually been found sufficient.

An important advantage possessed by the form of construction adopted in the spectrograph is that of adaptability for different regions of the spectrum. The prisms are mounted in cast-iron cells which rest upon three legs. These pass through slotted openings in the main plate of the spectrograph and are clamped rigidly with nuts upon the other side of the plate. The slotted openings are provided with scales and the prism mounting has upon it an index by which they may be read. The scale-readings for each prism were determined when the three prisms were originally adjusted for minimum deviation at a definite wave-length, and in case it is desired to set the prisms for any other wave-length, changes are made in the scale-readings corresponding to the difference of deviation. Similarly the camera is mounted on a heavy iron plate which swings through an angle corresponding to that of the third prism, and is clamped in position by powerful bolts. This simple arrangement has proved most satisfactory in use.

The great length of the camera regularly employed with the single-prism arrangement and the difficulty of supporting it with sufficient rigidity led to the interposition of a mirror between the prism and the camera lens. In this way the camera may be left in the same position as that used when three prisms are employed. The objections to this proceeding are: first, the loss of light by reflection at the mirror; and, second, the difficulty of supporting the mirror with sufficient stability. The first objection is not very serious, since the mirror is entirely inclosed, and the silver coat deteriorates very slowly and may be kept in excellent condition. Under these conditions the reflecting power for the region of the spectrum usually photographed is not far from 90 per cent. The second objection is met by making the mirror exceptionally thick and holding it in a strong cell in much the same way as a diffraction grating is supported. The photographs obtained with the spectrograph have shown no impairment as regards definition or accuracy of results since the mirror was employed. When two prisms are used the mirror cell is moved toward the camera lens along a slide provided with a graduated scale and is clamped in position.

For comparison spectrum purposes the iron arc is used. The arc lamp is fastened to the outside of the spectrograph case. The light passes through a mica window and falls upon a lens which renders it roughly parallel. This throws it upon a piece of opal glass which thoroughly diffuses it, and an image of this glass is thrown upon the slit by a second lens. The glass, accordingly, serves as the effective source of illumination for the spectrograph. A totally reflecting prism, which is moved in front of the slit by a handle on the outside of the spectrograph, serves to reflect the light into the instrument. An occulting screen with small openings through which the light from the star or from the arc may fall upon the slit also is controlled by a rod projecting from the side of the spectrograph.

The entire spectrograph is inclosed in a wooden case, the walls around the prism-box being of double construction. For purposes of automatic temperature control the convenient device first employed by Professor Campbell has been adopted, a pair of Draper thermostat strips with platinum contacts acting through a relay to throw the heating current on and off. The heating coils are placed outside of the first wall of the prism-box and are distributed as symmetrically as possible about it. A small fan placed inside of the outer cover serves to distribute the air around the outside of the prism-box and prevents stratification. When the instrument is under temperature control, readings of a thermometer placed inside the prism-box indicate ranges of temperature rarely greater than 0°.1 to 0°.2 C. throughout an entire night.

For guiding purposes we have used the customary device of a reflecting slit, the jaws being inclined at an angle of about 2°.5 to the normal. The reflected light is first collimated by a small lens and then reflected by diagonal prisms through a long tube to a point beneath the spectrograph where it is observed through a telescope. The arrangement is very similar to that employed by Professor Frost on the Bruce spectrograph. A finder of 4 m focal length attached to the tube of the large reflector is used to bring the star within the field of view. The observer keeps the star upon the slit by means of slow-motion motors controlled by switch buttons arranged upon a fiber bar held in his hand. Similar buttons control a motor at the upper end of the telescope tube which moves the convex mirror inward or outward and thus enables the observer to correct for changes of focus during the night. If the large mirror has been protected throughout the day by the canopy, as is regularly the case, these changes are rarely of large amount unless there is a marked change of temperature during the night.

This brief description of the general features of the spectrograph is perhaps sufficient to give a satisfactory conception of the instrument as a whole. Plate XII shows the spectrograph attached to the 60-inch reflector. A part of the outer cover has been removed as well as both covers to the prism-box, so that the arrangement of the prisms and of the camera and collimating tubes is well shown. The tube through which the light reflected from the slit is observed is seen beneath the spectrograph in the lower right-hand corner of the photograph.

PROGRAM OF WORK AND EXPOSURE TIMES

A large part of the time of the spectrograph during the year it has been in operation has been devoted to a determination of the radial velocities of some selected lists of stars, mainly of types A and B, whose proper motions have been measured by Boss and whose velocities are of especial importance in studies of star streams. The lists have been prepared by Professor Kapteyn and consist of stars which for the most part lie between magnitudes 5.5 and 6.5,[1] although a few are brighter. The experience of numerous observers of stellar spectra has shown that by far the greater number of stars with spectra of types A or B can be studied to better advantage with moderate dispersion and linear scale than with high dispersion, on account of the diffuse and broad character of their lines. Some experiments with our spectrograph showed that an optical system consisting of two prisms and the 46 cm camera, or a single prism and the 102 cm camera, gave the most satisfactory results for the majority of the stars. Both combinations have been used and as between the two it is largely a question of the type of spectrum and conditions of seeing. For stars with numerous lines in their spectra the greater resolving power of the two-prism arrangement is preferable. For stars with few lines, however, the single prism is adequate, and the greater width of spectrum obtained with the long camera is an important advantage. In fact, under good conditions of seeing the time occupied in running the star's image along the slit sufficiently to obtain a measurable width of spectrum

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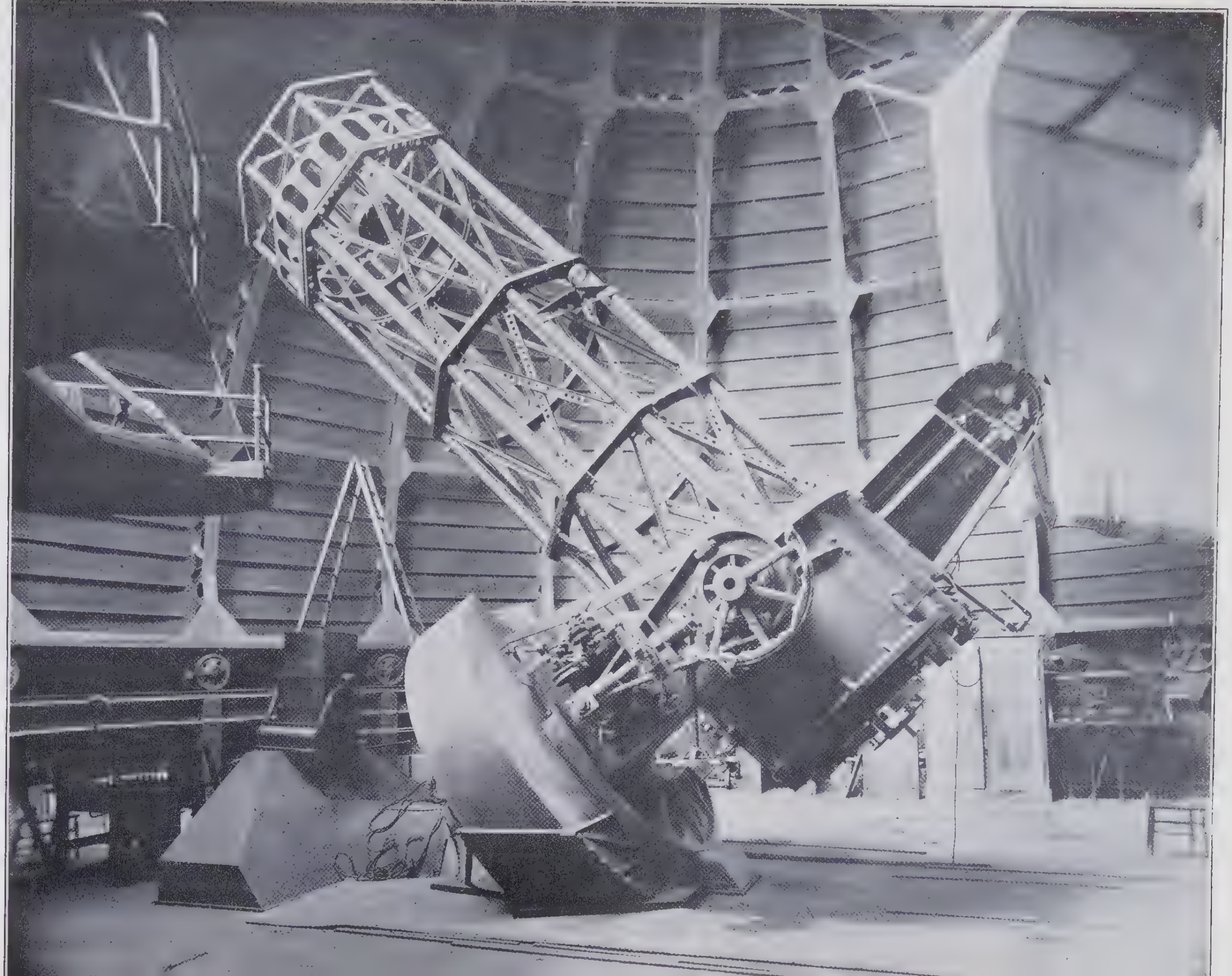
[1] The magnitudes used in this article are those given in the "Preliminary General Catalogue of 6188 Stars for the Epoch 1900," by Lewis Boss, *Carnegie Institution of Washington Publication* No. 115. A comparison of these magnitudes with those of the Potsdam and the Harvard Photometry is given in the "Catalogue."



is a considerable drawback to the use of the short camera. The linear scale at $H\gamma$ of the photographs obtained with the two arrangements is as follows:

Two prisms and short camera,	1 mm = 18.0 Ångströms
One prism and long camera,	1 mm = 15.7 Ångströms

The three prisms and long camera as used for the spectra of the brighter stars give a linear scale at $H\gamma$ of 1 mm = 5.2 Ångströms.

The exposure times with the spectrograph vary widely, of course, with the conditions of seeing. Under good conditions, when the silver surfaces of the telescope are bright, a fully timed negative of a star of type A or B of magnitude 6.0 on Boss's system may be obtained in one hour, when one prism and the long camera are employed. The exposure times with two prisms and the shorter camera are slightly less. Under average conditions the exposure times are somewhat longer, and under the poorest conditions of the winter season may be several times as long. Usually an exposure about one-fourth longer is given to stars of types F, G, K, and M than to stars of types A and B. The difference would be greater but for the fact that the density of negative required for satisfactory measurement is less in the case of spectra containing numerous lines than for those of types A and B. Under very good conditions of seeing, a fully timed negative of *Groombridge 1830* (Mag. 6.5, Spectrum G) has been obtained in 75 minutes with a slit-width of 0.050 mm. A narrower slit has been employed upon some nights of exceptionally fine seeing, but this width has been used for a majority of the photographs.

METHOD OF REDUCTION

The range of spectrum in good focus upon the negatives and upon which measures may be made extends from about λ 4250 to λ 4900. As a rule in the case of stars of types A and B the measures are limited to the portion between $H\gamma$ and $H\beta$. Within this region fall several of the most important helium lines, the magnesium line λ 4481, and a large number of enhanced metallic lines whose appearance is so characteristic of a portion of the A-type stars. The fact that $H\gamma$ and $H\beta$ are almost without exception measurable lines in the spectra of A- and B-type stars has led us to the use of auxiliary tables which have enabled us to save much time in the reduction of the photographs.

The method employed is that used by Professor Frost and several other observers, in accordance with which each negative is reduced independently from measures of three standard lines in the comparison spectrum. It has the marked advantage of requiring no adjustment of the measures on account of changes of focus of the camera or collimator or variation in the scale of the spectrum due to the different temperatures of the prism-train. The chief objection to it is the amount of time required to compute the constants of the Cornu-Hartmann formula for each plate. For the reduction of our spectrograms we have constructed tables giving the values of these constants for the entire range of variation of scale which may occur. This is accomplished in the following way. Two suitable comparison lines are selected at the extremities of the region measured and another line intermediate between them, and these lines are measured upon all of the photographs. The lines selected for our purposes are λ 4337.216 near $H\gamma$, λ 4859.928 near $H\beta$, and the intermediate line λ 4531.327. Let us indicate these lines by λ'', λ, and λ', and the corresponding readings of the comparator by S'', $S+\delta$, and S', as follows:

4859.928	λ	$S+\delta$
4531.327	λ'	S'
4337.216	λ''	S''

The solution of the Hartmann formula gives for the values of the constants:

$$\lambda_0=\lambda-\frac{a(\lambda-\lambda'')-b(\lambda-\lambda')}{a-b+\delta(\lambda'-\lambda'')},$$

$$S_0=\frac{aS'-bS''-\delta S'(\lambda-\lambda')+\delta S''(\lambda-\lambda'')}{a-b+\delta(\lambda'-\lambda'')},$$

$$C=(\lambda''-\lambda_0)(S''-S_0),$$

where $a=(\lambda-\lambda')\ (S''-S)$ and $b=(\lambda-\lambda'')\ (S'-S)$.

If we develop the values λ_0 and S_0 into series we obtain:

$$\lambda_0=\lambda-\alpha(1-\beta\delta+\beta^2\delta^2-\ \ldots\ .)$$
$$S_0=c-d\delta+d^2\delta^2-\ \ldots\ .$$

in which α, β, c, and d are constants. Both series are rapidly convergent for small values of δ. It is, of course, a simple matter to adjust all of the spectrograms under the comparator in such a way that the reading upon λ 4337 shall always be the same, or S'' constant. Then for any value of $S'-S''$ we may obtain the values of λ_0 and S_0 corresponding to a set of readings $S+\delta$ from the series given above. Since δ never exceeds 0.025 mm for our photographs the term δ^3 is negligible, and if extreme values of λ_0 and S_0 are known, all intermediate values may be obtained by simple interpolation in which the second differences are constant. To illustrate the construction of a page of the tables we may consider a specific case. Let the readings be:

4859.928	56.500 $+\delta$
4531.327	41.317
4337.216	30.000

A range in δ of 0.025 will readily take care of all the differences which may arise in the reading upon λ 4859 for a given reading upon λ 4531. Accordingly three Hartmann formulae are solved for readings of 56.500, 56.512, and 56.525. With these values of λ_0, S_0, and C we derive the values of the first and second differences for purposes of interpolation, and are enabled to compute rapidly the values of λ_0, S_0, and C corresponding to 56.501, 56.502, etc. This page of the table corresponds to the argument $S'-S''=11.317$. For the value $S'-S''=11.318$ a second page is computed, and the process is repeated throughout the range of scale which may occur. The measurement of a few photographs taken at different temperatures gives sufficient knowledge of the mean values about which the table should be constructed. In the case of our own photographs a table consisting of forty pages has been found sufficient to care for the entire range of variation of scale observed, and a table of this size was completed by a single computer with the aid of a calculating machine in about six days.

The constants of reduction for a given spectrogram being obtained by inspection from this table, the wave-lengths of the stellar and comparison lines are computed in the usual way from the constants, and the stellar wave-lengths are corrected according to the deviations of the comparison lines. The complete reduction of a spectrogram containing fifteen stellar and comparison lines occupies about twenty minutes.

TABLE I

Stars of Variable Radial Velocity

Boss Number Designation R.A. (1910) Dec. (1910)	Mag. and Type	No. of Plate	Observer	Date	G. M. T.	Radial Velocity	Measured by	Quality	Remarks
					h m	km			
Boss 67	5.6	29	A.	1910, Dec. 20	16 17	+ 5	L.	Fair	
Groom. 58	B 5	36	P.	1910, Dec. 21	15 32	− 35	L.A.		
$0^{h}19^{m}.4$		161	A.P.	1911, Jan. 21	16 18	0	L.A.		
$+51^{\circ}31'$		944	K.	1911, Dec. 11	15 19	+ 2	L.E.		
		988	A.	1912, Jan. 7	15 34	− 4	L.		
Boss 68	5.6	25	A.	1910, Dec. 18	16 14	− 18	L.	Poor	
12 Cassiop.	B 9	37	P.	1910, Dec. 21	16 42	− 49	L.A.		
$0^{h}19^{m}.8$		160	A.	1911, Jan. 21	15 34	− 12	L.A.		
$+61^{\circ}20'$		934	K.	1911, Dec. 9	17 10	+ 5	L.E.		
		1009	A.	1912, Jan. 11	15 24	− 19	L.		
Boss 91	5.4	624	P.	1911, Aug. 13	22 15	− 3	L.E.	Fair	
49 G Ceti	A 2	859	K.	1911, Oct. 13	19 42	+ 15	L.E.A.		
$0^{h}25^{m}.9$		915	K.	1911, Nov. 5	16 48	+ 32	L.E.A.		
$-24^{\circ}17'$									
Boss 159	5.5	30	A.	1910, Dec. 20	17 08	+ 18	L.	Fair	
23 Cassiop.	B 9	38	P.	1910, Dec. 21	17 40	− 30	L.A.		
$0^{h}41^{m}.7$		135	A.	1911, Jan. 18	15 22	− 16	L.A.		
$+74^{\circ}21'$		874	A.	1911, Oct. 30	20 05	+ 3	L.E.K.		
		935	K.	1911, Dec. 9	18 16	+ 5	L.E.		
		981	K.	1912, Jan. 5	15 55	+ 11	L.E.		
Boss 412	5.7	138	B.	1911, Jan. 18	17 37	+ 77	L.A.	Poor	
1 Persei	B 3	876	A.	1911, Oct. 30	22 05	− 12	L.A.		
$1^{h}46^{m}.1$		945	K.	1911, Dec. 11	16 20	− 6	L.E.		
$+54^{\circ}42'$		989	A.	1912, Jan. 7	17 40	− 23	L.E.		

Boss 425	5·2	20	A.	1910, Dec. 17	15 30	+ 12	L.A.	Good	
ω Cassiop.	B 9	139	B.	1911, Jan. 18	18 42	− 46	L.A.		
$1^{h}49^{m}.0$		148	A.	1911, Jan. 19	18 25	− 44	L.A.		
+68°15′		995	A.	1912, Jan. 8	17 00	− 41	L.E.		
Boss 522	5·4	710	K.	1911, Sep. 9	21 37	− 40	L.E.	Fair	Probably composite spectrum
62 Andromedae	A	766	K.	1911, Sep. 17	21 18	− 21	L.E.		
$2^{h}13^{m}.5$		801	A.	1911, Oct. 6	21 45	− 22	L.E.A.K.		
+46°58′									
Boss 641	5·5	70	P.	1910, Dec. 24	16 38	− 9	L.A.	Good	
π Arietis	B 5	146	A.	1911, Jan. 19	16 48	− 12	L.A.		
$2^{h}44^{m}.2$		209	A.	1911, Feb. 10	15 51	+ 32	L.E.		
+17°5′		951	K.	1911, Dec. 12	15 50	+ 7	L.E.		
Boss 731	5·7	711	K.	1911, Sep. 9	22 39	− 4	L.E.	Good	Probably composite spectrum
Piazzi 9	A	767	K.	1911, Sep. 17	22 19	− 8	L.E.		
$3^{h}9^{m}.8$		820	A.	1911, Oct. 8	21 46	− 17	L.E.A.		
+30°13′		860	K.	1911, Oct. 13	21 30	− 4	L.E.A.		
		959	K.	1911, Dec. 14	18 00	+ 2	L.E.		
Boss 740	5·5	12	A.	1910, Dec. 16	17 02	+ 23	L.A.	Poor	
30 Persei	B 5	32	A.	1910, Dec. 20	18 42	+ 12	L.A.		
$3^{h}11^{m}.7$		40	P.	1910, Dec. 21	19 28	− 6	L.A.		
+43°42′		77	P.	1911, Jan. 7	15 15	− 14	L.A.		
		87	P.	1911, Jan. 8	14 36	+ 11	L.A.		
Boss 796	6.1	33	A.	1910, Dec. 20	19 40	+ 24	L.A.	Poor	
Brad. 480	B 8	41	P.	1910, Dec. 21	20 30	+ 2	L.A.		
$3^{h}24^{m}.2$		97	P.	1911, Jan. 11	17 43	− 1	L.A.		
+47°48′		107	P.	1911, Jan. 12	18 01	+ 13	L.A.		
Boss 841	5·7	51	P.	1910, Dec. 22	18 12	− 59	L.A.	Poor	
13 Tauri	B 8	177	A.	1911, Feb. 7	16 12	+ 9	L.W.		
$3^{h}37^{m}.1$		997	A.	1912, Jan. 8	19 05	+ 8	L.E.		
+19°25′									

TABLE I—*Continued*

Boss Number Designation R.A. (1910) Dec. (1910)	Mag. and Type	No. of Plate	Observer	Date	G. M. T.	Radial Velocity	Measured by	Quality	Remarks
					h m	km			
Boss 857	5.4	62	P.	1910, Dec. 23	17 28	+ 61	L.A.	Poor	
24 Eridani	B 8	110	P.	1911, Jan. 12	18 44	+ 75	L.A.		
$3^h39^m.9$		127	B.	1911, Jan. 17	16 24	+ 41	L.A.		
$-1°29'$									
Boss 878	5.3	724	A.	1911, Sep. 11	22 40	− 19	L.E.	Good	
42 Persei	A 2	790	A.	1911, Oct. 5	23 14	+ 13	L.E.A.		
$3^h43^m.8$		891	A.	1911, Nov. 1	21 25	− 7	L.		
$+32°49'$		967	K.	1911, Dec. 30	18 42	− 40	L.E.K.		
Boss 992	5.6	35	A.	1910, Dec. 20	21 59	− 35	L.A.	Poor	
Groom. 809	B 3	42	P.	1910, Dec. 21	21 46	+ 3	L.A.		
$4^h13^m.4$		180	A.	1911, Feb. 7	18 41	− 42	L.W.A.		
$+50°42'$		271	A.	1911, Mar. 15	15 29	− 7	L.A.		
		1007	A.	1912, Jan. 9	19 35	− 40	L.E.		
Boss 1076	4.4	826	K.	1911, Oct. 9	21 48	− 43	L.E.A.	Good	
88 Tauri	A 2	904	K.	1911, Nov. 3	22 31	− 40	L.E.A.		
$4^h30^m.7$		984	K.	1912, Jan. 5	19 54	+ 71	L.E.		
$+9°59'$									
Boss 1249	6.0	211	A.	1911, Feb. 11	18 06	+ 61	L.	Good	Two spectra present, B 5 and probably A 3. Measures on stronger spectrum B 5
Pulk. 801	B 5 p	272	A.	1911, Mar. 15	16 30	+ 64	L.A.W.		
$5^h10^m.4$		281	A.	1911, Mar. 16	16 26	+ 53	L.A.		
$+34°13'$		309	P.	1911, Mar. 24	16 20	+ 63	L.W.		
		936	K.	1911, Dec. 9	20 38	+ 53	L.E.		
		998	A.	1912, Jan. 8	20 13	+ 64	L.E.		
Boss 1349	5.6	64	P.	1910, Dec. 23	19 18	+134	L.A.	Fair	
Green. 412 (1860)	B 2	112	P.	1911, Jan. 12	21 28	−138	L.A.		
$5^h28^m.9$									
$-1°13'$									

Boss 1607 Groom. 1149 $6^{h}18^{m}.8$ $+56^{\circ}20'$	5·7 A 5	877	A.	1911, Oct. 30	23 02	− 55·8	L.E.A.	Good	
		910	K.	1911, Nov. 4	22 08	+ 21·2	L.E.A.		
		949	K.	1911, Dec. 11	23 28	− 75·8	L.E.		
Boss 1906 Brad. 1056 $7^{h}15^{m}.5$ $+55^{\circ}29'$	5·9 B 8	68	P.	1910, Dec. 23	23 10	− 80	L.A.	Fair	Two spectra present
		103	P.	1911, Jan. 11	23 40	+ 90	L.A.		
		132	B.	1911, Jan. 17	21 58	− 6	L.A.		
Boss 2400 *62 Cancri* $8^{h}52^{m}.2$ $+15^{\circ}40'$	5·3 A 3	930	K.	1911, Dec. 8	23 11	− 46	L.E.	Good	
		969	K.	1911, Dec. 30	23 08	− 35	L.E.K.		
		1025	K.	1912, Jan. 24	21 58	− 13	L.E.A.		
Boss 2407 *a Cancri* $8^{h}53^{m}.6$ $+12^{\circ}12'$	4·4 A 3	923	K.	1911, Dec. 7	1 08	− 54	L.E.	Good	
		931	K.	1911, Dec. 8	23 56	− 59	L.E.		
		1026	K.	1912, Jan. 24	22 50	− 21	L.E.A.		
Boss 2451 *19 Hydrae* $9^{h}4^{m}.3$ $-8^{\circ}14'$	5·6 B 8	191	A.	1911, Feb. 8	19 24	+ 14	L.E.A.	Poor	
		202	A.	1911, Feb. 9	19 38	+ 18	L.W.A.		
		256	A.	1911, Mar. 11	18 16	+ 46	L.A.		
		392	A.	1911, May 9	16 10	+ 4	L.A.		
Boss 2866 *42 Leo. Min.* $10^{h}40^{m}.9$ $+31^{\circ}9'$	5·4 B 9	75	P.	1910, Dec. 25	0 03	− 2	L.A.	Poor	
		104	P.	1911, Jan. 12	1 20	+ 40	L.A.		
		157	A.	1911, Jan. 20	0 40	− 9	L.A.		
Boss 3123 *95 Leonis* $11^{h}51^{m}.0$ $+16^{\circ}9'$	5·7 A 2	950	K.	1911, Dec. 21	0 32	− 90	L.E.	Fair	
		1027	K.	1912, Jan. 25	0 01	+ 7	L.E.A.		

TABLE I—*Continued*

Boss Number Designation R.A. (1910) Dec. (1910)	Mag. and Type	No. of Plate	Observer	Date	G. M. T.	Radial Velocity	Measured by	Quality	Remarks
					h m	km			
Boss 3138	5.4	183	A.	1911, Feb. 7	22 34	+ 16	L.W.	Good	
31 Crateris	B 3	258	A.	1911, Mar. 11	20 26	−116	L.A.		
$11^{h}56^{m}.2$		311	P.	1911, Mar. 24	20 15	+ 85	L.A.		
$-19^{\circ}9'$		348	A.	1911, Apr. 12	18 56	− 21	L.E.		
Boss 3546	6.4	302	B.	1911, Mar. 19	22 22	+ 11	L.A.	Poor	
85 Virginis	B 9	312	P.	1911, Mar. 24	22 00	− 93	L.A.		
$13^{h}40^{m}.7$									
$-15^{\circ}19'$									
Boss 3915	5.6	363	A.	1911, Apr. 14	21 30	+ 16	L.E.A.	Poor	
50 Boötis	B 9	509	A.	1911, July 6	18 38	− 3	L.E.A.		
$15^{h}18^{m}.2$		539	B.	1911, July 11	16 41	− 41	L.E.A.		
$+33^{\circ}15'$									
Boss 3944	5.7	303	P.	1911, Mar. 19	23 55	− 23	L.E.A.	Poor	Possibly composite spectrum
35 Librae	B 3	314	P.	1911, Mar. 24	23 39	− 19	L.A.		
$15^{h}27^{m}.8$		489	A.	1911, June 17	15 57	+ 30	L.A.E.		
$-16^{\circ}33'$									
Boss 3993	5.3	232	B.	1911, Feb. 17	0 30	+ 3	L.W.	Good	
χ Serpentis	A 3 p	333	P.	1911, Apr. 9	20 47	− 4	L.		
$15^{h}37^{m}.6$		478	A.	1911, June 15	16 10	+ 36	L.A.		
$+13^{\circ}8'$									
Boss 4097	5.8	359	A.	1911, Apr. 13	22 22	− 13	L.	Poor	
11 Scorpii	B 9	496	A.	1911, July 4	17 45	− 30	L.E.A.		
$16^{h}2^{m}.6$		527	A.	1911, July 9	16 40	− 6	L.E.		
$-12^{\circ}30'$		533	A.	1911, July 10	17 19	− 50	L.E.A.		

Boss 4353 Piazzi 303 $17^{h}3^{m}6$ −0°58′	6.2 A	442 464 497 540	B. P. A. B.	1911, June 10 1911, June 11 1911, July 4 1911, July 11	21 26 19 48 19 07 17 56	− 14 − 21 − 39 − 8	L.A. L.E.A. L.A. L.E.A.	Fair	
Boss 4402 *70 Herculis* $17^{h}17^{m}2$ +24°35′	5.5 A	674 726 812	B. K. A.	1911, Sep. 6 1911, Sep. 12 1911, Oct. 8	60 00 15 22 15 10	− 18 − 26 − 3	L.E. L.E.A. L.E.A.	Fair	
Boss 4643 *108 Herculis* $18^{h}17^{m}5$ +29°49′	5.7 A 3	660 714 813 822	B. K. A. K.	1911, Sep. 4 1911, Sep. 10 1911, Oct. 8 1911, Oct. 9	16 07 15 35 16 09 15 25	− 94 − 62 − 28 + 38	L.E.A. L.E. L.E.A. L.E.A.	Good	
Boss 4867 Piazzi 318 $19^{h}3^{m}0$ +28°29′	5.7 A 3	667 728 906	B. K. K.	1911, Sep. 5 1911, Sep. 12 1911, Nov. 4	16 59 16 36 15 00	− 42 − 6 − 24	L.E.A. L.E.A. L.E.K.	Poor	Probably composite spectrum
Boss 4947 *2 Sagittae* $19^{h}20^{m}3$ +16°46′	6.2 A 3	591 879	B. A.	1911, Aug. 9 1911, Oct. 31	18 21 15 46	+ 61 + 18	L.E. L.E.A.	Good	
Boss 5042 *ψ Aquilae* $19^{h}40^{m}4$ +13°5′	6.4 A p	629 720 763	P. K. K.	1911, Aug. 14 1911, Sep. 11 1911, Sep. 17	19 18 17 29 17 20	− 27 − 2 + 16	L.E.A. L.E.A. L.E.	Good	
Boss 5113 Groom. 2984 $19^{h}54^{m}1$ +40°8′	5.6 B 3	518 886	A. A.	1911, July 7 1911, Nov. 1	21 44 15 32	− 65 + 23	L.E.A. L.E.A.	Poor	

TABLE I—*Continued*

Boss Number Designation R.A. (1910) Dec. (1910)	Mag. and Type	No. of Plate	Observer	Date	G. M. T.	Radial Velocity	Measured by	Quality	Remarks
					h m	km			
Boss 5178	6.0	519	A.	1911, July 7	22 44	− 16	L.E.A.	Poor	$H\beta$ doubly reversed
20 Vulpeculae	B 8 p	536	A.	1911, July 10	20 48	− 32	L.E.A.		
$20^{h}8^{m}.2$		552	B.	1911, July 13	20 36	− 37	L.E.A.		
$+26^{\circ}13'$		796	A.	1911, Oct. 6	17 50	− 15	L.A.K.		
Boss 5211	5.8	691	B.	1911, Sep. 7	18 58	+ 2	L.E.A.	Fair	
36 Cygni	A	738	K.	1911, Sep. 14	18 13	− 27	L.E.A.		
$20^{h}15^{m}.1$		823	K.	1911, Oct. 9	17 03	− 10	L.E.A.		
$+36^{\circ}43'$									
Boss 5292	5.5	706	K.	1911, Sep. 9	17 51	+ 45	L.E.A.	Good	
ι Delphini	A 2	770	K.	1911, Sep. 18	18 06	+ 18	L.E.		
$20^{h}33^{m}.5$		894	A.	1911, Nov. 2	15 08	+ 24	L.E.A.		
$+11^{\circ}4'$									
Boss 5322	5.8	692	B.	1911, Sep. 7	20 12	− 40	L.E.	Good	
Groom. 3258	B 9	755	K.	1911, Sep. 16	17 59	− 25	L.E.		
$20^{h}38^{m}.7$		914	K.	1911, Nov. 5	15 34	− 16	L.E.A.		
$+41^{\circ}24'$									
Boss 5573	6.2	593	B.	1911, Aug. 9	21 25	+ 33	L.E.	Fair	
76 Cygni	B 9	640	P.	1911, Aug. 15	21 48	− 7	L.E.		
$21^{h}38^{m}.0$									
$+40^{\circ}18'$									
Boss 5581	6.2	588	B.	1911, Aug. 8	20 40	+ 23	L.E.	Poor	
45 Capricorni	A 2	621	P.	1911, Aug. 13	19 40	+ 45	L.E.		
$21^{h}39^{m}.1$		654	P.	1911, Aug. 17	19 34	− 3	L.E.A.		
$-15^{\circ}10'$									

Boss 5692 *25 Pegasi* $22^{h}3^{m}.6$ $+21^\circ16'$	5.9 B 5 p	852	K.	1911, Oct. 12	18 23	− 55	L.E.A.	Fair	*Hβ* bright
		887	A.	1911, Nov. 1	16 48	− 59	L.E.A.		
		954	K.	1911, Dec. 13	15 32	− 36	L.E.		
Boss 5738 Br. 2938 $22^{h}11^{m}.0$ $+62^\circ43'$	6.4 B 8	601	B.	1911, Aug. 10	22 08	− 15	L.E.A.	Poor	
		858	K.	1911, Oct. 13	17 36	+ 28	L.E.A.		
Boss 5833 *8 Lacertae* $22^{h}31^{m}.9$ $+39^\circ10'$	5.9 Oe p	608	B.	1911, Aug. 11	22 16	− 39	L.E.A.	Poor	*Hβ* unsymmetrically reversed
		632	P.	1911, Aug. 14	22 22	+ 7	L.E.		
		807	A.	1911, Oct. 7	19 44	+ 4	L.A.K.		
Boss 5848 *30 Cephei* $22^{h}35^{m}.5$ $+63^\circ7'$	5.3 B 9	732	K.	1911, Sep. 12	21 42	+ 40	L.E.A.	Poor	
		784	A.	1911, Oct. 5	18 24	− 5	L.E.A.K.		
		866	K.	1911, Oct. 14	17 30	+ 16	L.E.A.		
Boss 5856 *12 Lacertae* $22^{h}37^{m}.5$ $+39^\circ45'$	5.4 B 2	648	P.	1911, Aug. 16	23 00	+ 3	L.E.	Good	
		702	K.	1911, Sep. 8	21 49	+ 6	L.E.A.		
		756	K.	1911, Sep. 16	19 03	− 8	L.E.		
		786	A.	1911, Oct. 11	19 34	− 43	L.E.		
Boss 6075 *18 Andromedae* $23^{h}34^{m}.8$ $+49^\circ58'$	5.4 B 8	602	B.	1911, Aug. 10	23 28	+ 37	L.E.A.	Poor	
		633	P.	1911, Aug. 14	23 30	− 3	L.E.		
		659	P.	1911, Aug. 18	0 07	− 1	L.E.A.		
		799	A.	1911, Oct. 6	19 56	+ 1	L.E.A.		
Boss 6142 Br. 3184 $23^{h}51^{m}.0$ $+56^\circ55'$	6.2 Oe p	888	A.	1911, Nov. 1	18 12	− 53	L.E.A.	Fair	Spectrum probably composite
		987	A.	1912, Jan. 6	15 54	− 11	L.E.		
		1003	A.	1912, Jan. 9	15 12	−133	L.		

SOME RESULTS

A list of fifty spectroscopic binaries.—We have found the above 50 stars mainly of types A and B to have variable velocities in the line of sight. The initial given in the column headed "Observer" refers to Messrs. Adams, Babcock, Kohlschütter, and Pease, and in the column "Measured by" to Miss Lasby, Miss Ensign, Miss Waterman, and Messrs. Kohlschütter and Adams. The type of spectrum given is in most cases from our own observations. The column in the table preceding "Remarks" indicates roughly the general character of the spectrum for purposes of measurement. There is evidence of complexity of the hydrogen lines in the spectra of many of these stars, and no doubt more would be found were the density of the negatives made somewhat less. As a rule, however, considerable density of the continuous spectrum aids in the measurement of the broad hazy lines characteristic of the spectra of most of these stars.

In addition to the stars given in Table I we have secured observations which agree in confirming the variability of velocity of the following stars announced from other observatories:

Name	R. A. 1910	Dec. 1910	Mag.	Observatory
25 Serpentis...........	$15^{h}41^{m}.4$	− 1°31′	5.6	Yerkes
χ Ophiuchi...........	16 21.8	−18°14′	4.8	Lick
ζ′ Lyrae..............	18 41.7	+37°31′	4.4	Lick
δ^1 Lyrae..............	18 50.6	+36°52′	5.7	Yerkes
θ Aquilae............	20 6.7	− 1° 5′	3.2	Meudon
6 Lacertae............	22 26.6	+42°40′	4.5	Yerkes

Stars with bright hydrogen lines.—The stars *20 Vulpeculae*, *25 Pegasi*, and *8 Lacertae* in Table I have one or more hydrogen lines bright. In *χ Ophiuchi*, as has been announced by Professor Campbell, both $H\gamma$ and $H\beta$ are bright. The following stars also have bright hydrogen lines:

Name	R. A. 1910	Dec. 1910	Mag.	Bright Lines
11 Camelopardalis	$4^{h}58^{m}.3$	+58°51′	5.3	$H\gamma$ *and* $H\beta$
165 G Canis Majoris ...	7 20.6	−16° 1′	5.3	$H\gamma$ *and* $H\beta$
25 Vulpeculae........	20 18.2	+24°10′	5.7	$H\beta$

TABLE II

Stars with Great Radial Velocities

Designation R.A. (1910) Dec. (1910)	Mag. Spectrum	No. of Plate	Observer	Date	Radial Velocity	Mean Radial Velocity	Velocity in Space	Angle to Line of Sight
					km	km	km	
Lal. 4855 $2^{h}33^{m}.3$ $+30^{\circ}28'$	7.2 G	β 74	A.	1910, Jan. 18	−120	−120	186	130°
Lal. 5761 $3^{h}3^{m}.1$ $+26^{\circ}\ 0'$	8.0 F	β 75	A.	1910, Jan. 18	−156			
		β 91	A.	1910, Feb. 18	−153			
		β 104	A.	1910, Feb. 21	−150	−153	188	144°
Groom. 864 $4^{h}35^{m}.2$ $+41^{\circ}58'$	7.3 G	β 81	A.	1910, Jan. 21	+103			
		β 86	A.	1910, Feb. 17	+102			
		β 97	A.	1910, Feb. 20	+101			
		β 105	A.	1910, Feb. 21	+ 97			
		γ 237	P.	1911, Feb. 18	+100.8			
		γ 245	P.	1911, Feb. 21	+103.7	+101	163	52°
Groom. 1830 $11^{h}47^{m}.7$ $+38^{\circ}23'$	6.5 G	γ 194	A.	1911, Feb. 8	− 99.7			
		γ 247	P.	1911, Feb. 21	− 99.2			
		γ 362	A.	1911, Apr. 14	− 96.2			
		γ 399	A.	1911, May 11	− 95.8	− 97.7	343	107°
Lal. 28607 $15^{h}38^{m}.2$ $-10^{\circ}39'$	7.3 A	γ 323	P.	1911, Apr. 7	−166			
		γ 368	A.	1911, Apr. 15	−168			
		γ 446	B.	1911, June 7	−172			
		γ 516	A.	1911, July 7	−175	−170	173	128°
31 b Aquilae $19^{h}20^{m}.7$ $+11^{\circ}45'$	5.2 G	γ 335	P.	1911, Apr. 9	− 95.9			
		γ 377	A.	1911, Apr. 16	− 97.0	− 96.4	119	144°
Lal. 37120–1 $19^{h}30^{m}.1$ $33^{\circ}\ 0'$	6.6 G	β 227	A.	1910, May 20	−162			
		β 235	A.	1910, May 21	−163			
		γ 364	A.	1911, Apr. 14	−161.9			
		γ 409	P.	1911, May 15	−161.8	−162	167	166°

Some stars with great radial velocities.—In the course of our observations of some stars of large proper motions with known parallaxes we have found a few stars with very great radial velocities. Most of these had previously been observed with the small focal plane spectrograph and approximate velocities determined. Accordingly in Table II the spectrograms obtained with the focal plane instrument are indicated by the series letter β and those with the large spectrograph by γ. The values obtained with the small spectrograph are of course subject to considerable uncertainty.

With the exception of *Groombridge 1830*, for which Professor Campbell has published a value of -95 km, no other observations are available for these stars. The star *Lalande 28607* is of especial interest because of its type of spectrum. No star of type A with a constant velocity approaching this in magnitude has been observed heretofore.

Since the parallaxes and the proper motions of these stars are known, a computation of their velocities and directions of motion in space becomes of interest. These are given in the last two columns of Table II, the requisite data being taken from the list of parallax determinations compiled by Kapteyn and Weersma.[1]

I am indebted for much assistance in connection with the results referred to in this communication. In particular I wish to express my appreciation to Mr. Pease for his great aid in the design of the spectrograph, many important features of which are due to his suggestions; to Mr. Babcock and Dr. Kohlschütter for observations with the instrument; and to Miss Lasby, Miss Ensign, and Miss Waterman for the difficult work involved in the measurement of the spectra.

MOUNT WILSON SOLAR OBSERVATORY
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[1] *Publications of the Astronomical Laboratory of Groningen*, No. 24.

Contributions from the Mount Wilson Solar Observatory, No. 60
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THE EFFECT OF PRESSURE UPON ELECTRIC FURNACE SPECTRA

SECOND PAPER

By ARTHUR S. KING

In a former paper[1] the writer reported the results of some preliminary experiments on the spectrum of the electric furnace when operated in an atmosphere of compressed gas. The displacements measured were chiefly for lines in two regions of the iron spectrum for a pressure of 9 atmospheres. The measurements, though not extensive enough to be given high weight, showed, when compared with such measurements of arc spectra under pressure as were available, that the lines in general were displaced much more in the furnace than in the arc at equal pressure.

It was obviously desirable to continue this investigation in such a way as to establish in a definitive manner the leading characteristics of the furnace spectrum when under pressure, and it is believed that sufficient material is now on hand for this purpose. About one hundred furnace photographs have been made since the preliminary set, the spectra studied being those of iron for the regions λ 4200 to λ 4500 and λ 5200 to λ 5500, titanium from λ 4250 to λ 4600, and vanadium from λ 4050 to λ 4600. The range of pressures has been up to 24 atmospheres for the two regions of the iron spectrum, up to 16 atmospheres for the spectra of titanium and vanadium. The leading features studied have been as follows:

1. The rate of increase of displacement with pressure and the mean shift per atmosphere for various groups of lines which permitted measurements of considerable accuracy.

2. The pressure effect in absorption as obtained by passing white light through the furnace tube when under pressure.

3. A search for possible variation of displacement with temperature.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 53; *Astrophysical Journal*, **34**, 37, 1911.

4. The observation of the effects due to large and small quantities of the radiating vapor, to the presence of foreign vapors, and to variation in the length of the column of vapor by the use of long and short tubes, the pressure being the same for these different conditions.

5. A comparison of the relative displacements of groups of lines with their response to temperature excitation and with their behavior in the magnetic field.

6. A consideration in the case of a few iron lines of the variation of displacement with wave-length.

7. Attention is directed to what is apparently a fundamental difference in the structure of arc and furnace lines which may explain the difference in absolute displacement given by the two sources.

EXPERIMENTAL METHOD

The work has been carried on in general according to the method described in the previous paper, with such improvements as experience showed to be feasible. The photographs were made in the second order of the vertical Littrow spectrograph in the Pasadena laboratory, the scale for the regions studied ranging from 0.93 to 0.96 Å per mm. The furnace was operated in vacuum to give the comparison spectrum, which was placed on each side of the pressure photograph by means of the occulting plate above the slit. This exposure with the furnace in vacuum was taken partly before and partly after the pressure photograph, the second exposure being made with increased length of slit on each side, so that the comparison photograph appears as the superposition of the two exposures, with weak extensions due to the second. This gave an exceedingly delicate test for instrumental displacement during the making of the complete photograph, better than is given by a double exposure with slit unchanged in length since the fainter extensions sometimes showed a very slight lack of continuity when the superposed portion of the line did not appear to suffer in sharpness.

The tubes used in the furnace, except for the special tests at the close of the investigation, were of Acheson graphite, 30.5 cm long, 12.5 mm inside diameter, and either 19 or 20.5 mm outside diameter, 20.5 cm being heated between the graphite contact blocks which led in the current. The tube was protected by a split graphite tube and by carborundum powder outside of this.

For the compressed gas, both carbon dioxide and air were used, the latter for most of the work, as it gave better results than carbon dioxide, especially for pressures above 16 atmospheres. The writer was surprised to find that the oxygen furnished by the air seemed to be less than that given off by dissociation of the carbon dioxide when in contact with the hot tube and jacketing materials, as the tubes lasted better in air and less of the white smoke was generated which always proved very disturbing with carbon dioxide on account of weakening the light and clouding the window. A very efficient method of jacketing has been devised, so that there was little circulation of gas about the exterior of the tube and it wore thin slowly. As a rule the tube was renewed in preparation for each photograph which involved a run of the furnace under pressure and two comparisons in vacuum, but occasionally a tube could be used longer at moderate temperatures. In one case the same tube was used for three successive experiments, being heated for a total of 2^h 46^m in air at 16 atmospheres, besides comparisons in vacuum aggregating 1^h 6^m. The tubes appear to be much more subject to oxidation outside than inside, the oxygen entering the tube apparently passing into combination before it reaches the highly heated portion.

The best results were obtained for temperatures which gave readings of 2200° to 2400° C. when a Wanner pyrometer was directed at the wall of the interior of the tube. The temperature of the radiating vapor is necessarily lower than this by an unknown amount, since the temperature of the graphite wall, obtained either in this way or by the melting-point method, must be higher than that of the inclosed vapor.

The pressure was measured by a new calibrated gauge reading to 500 pounds. Two other gauges, which were used in former work and by Mr. Gale with the pressure arc, showed a close agreement with this gauge except at the beginning of their scales.

When the carborundum jacket was used, there was always a certain amount of vapor, especially at the higher pressures, which condensed as a white powder on the water-cooled metal parts. This was not tested chemically but was probably an oxide of some constituent of the carborundum. As has been noted, there was more of this vapor when compressed carbon dioxide was employed. Near the end of the investigation, it was desired to try the effect of foreign vapors purposely introduced and also of different lengths of the column of radiating vapor. In both cases this oxide from the jacketing would have complicated the conditions, so the experiments were made without any protection around the tube. Naturally, there was then a more rapid wearing-away of the tube and a very rapid loss of the heat to the water-cooled chamber and electrode pipes, requiring a large increase in the electric energy to keep up the temperature. It was possible, however, to make the desired series of experiments under these conditions for a pressure of 8 atmospheres.

Tubes for which the heated portion was only 51 or 64 mm long were used by setting the two contact blocks at the proper points along the copper-pipe electrodes. Other tubes with a total length of 35.5 cm, 25.5 cm being heated, were also employed.

A new method of studying the pressure effect, for which the furnace is especially adapted, was carried out by obtaining the lines under pressure as absorption lines. The comparison spectrum was obtained as usual, in emission, with the furnace in vacuum before and after the pressure exposure. For the pressure photograph a parallel beam of white light from a projection arc was directed by means of a short-focus lens into the window of the furnace opposite the spectrograph. This light passed through the vapor in the furnace tube, which was radiating under pressure, and thence to the spectrograph. Absorption lines are thus obtained which can be made very narrow if the continuous spectrum is strong. The temperature of the furnace tube may be low if only the stronger lines are desired, and the exposure time is much less than is required for the same lines in emission. The pressure displacements, as will be shown later, are in good agreement with those obtained when the tube is strongly excited so as to give self-reversed lines. The method promises to be very useful as a supplementary one, especially for spectra such as titanium, where a large number of lines are easily produced by the furnace but do not readily show self-reversal. The edges of the absorption lines are liable to be somewhat ragged as the result of the large variation in temperature from the middle to the two ends of the furnace tube, with attendant differences in density of the vapor. A strong continuous spectrum will remedy this to a large extent. Care must also be taken when examining lines which are also given as sharp emission lines by impurities in the carbons of the arc, since if the pressure displacement be small, the violet side of the absorption line is affected by the presence of the bright line.

In measuring the displacements, a series of four or six settings was made on the comparison line and a like number on the line displaced by pressure. The plate was then reversed in the machine and a similar set taken in the opposite direction. All plates of sufficiently good quality were measured by the writer on a small Gaertner comparator and most of them also by Miss Sheldon.

RESULTS

For the purpose of establishing the main phenomena of the pressure effect for the furnace, a set of lines was selected in the iron, titanium, and vanadium spectra which can be measured with fair precision at various pressures. As a rule (the exceptions usually being noted in the tables) only lines for iron and vanadium are measured which are distinctly reversed. For titanium the lines were measured unreversed and in absorption. The list is thus limited to lines appearing at the lower furnace temperatures, the self-reversal being given by the absorption of the cooler vapor at the ends of the tube. The former paper showed that the number of iron lines which can be measured in the furnace spectrum, especially at pressures less than 10 atmospheres, is quite comparable with the number measurable in the arc, and this is true also for titanium and vanadium, but special conditions must be chosen for various sets of lines, since on any one plate only a relatively small number of lines will yield measurements of high weight.

As there is always a certain amount of widening to pressure lines, which in general increases with the pressure and often involves dissymmetry in the widening, a reversed line is preferable for measurement, provided the reversal is narrow. If there is a tendency for the line to widen toward one side, the reversal may be expected to take part in this, but on account of its relatively small width, its position as measured cannot differ from the true position of the maximum by so great an amount as may easily happen when an unreversed and rather wide line is measured.

It is characteristic of reversed lines in furnace spectra that they do not have clean-cut edges to the reversals. There is a slow gradient in temperature and vapor-density from the center to each end of the tube which results in a gradual shading of the sides of the reversal. For this reason, personal judgment may enter to a considerable degree in making settings on the lines, and the opportunity for this increases if the reversals are not very narrow. Differences of considerable magnitude in the measurements for single lines have occasionally been observed which may fairly be ascribed to this cause. However, all of the conclusions to be drawn from the material in this paper are based on mean displacements for sets of lines which show shifts of the same order of magnitude, and such means do not appear to be greatly affected by personal differences. As a test, the mean displacements were compared for ten good plates measured by Miss Sheldon and myself. These plates embraced the spectra of all three elements and were for various pressures and different types of lines. The differences ranged from 9 per cent for unreversed titanium lines to exact agreement for a plate containing over 20 reversed vanadium lines. Most of the differences were well under 5 per cent and about equally divided as to which observer obtained the higher values. A large proportion of the whole number of plates was of about the quality of those compared, so that it seems highly improbable that the mean values presented are affected in any vital degree by peculiarities in personal judgment.

It was desirable to look farther into the large differences between furnace and arc displacements for the same pressure, which were indicated by the preliminary observations. Instrumental differences, such as must occur for work carried out in different laboratories, have been largely eliminated by comparing the later furnace results with the values for arc displacements obtained by Gale and

Adams[1] in an investigation carried out with pressures which were used also for the furnace and with the same spectrograph. At the close of the pressure-arc investigation, the spectrograph was used by the writer with the same adjustments as to focus, thus insuring that the photographs, as regards scale and definition, should be as closely comparable as possible. The change from the arc arrangements thus consisted in turning the vertical spectrograph around until its mirror faced the furnace. The image of the interior of the tube was focused on the slit, giving a cone of light slightly larger than the objective of the spectrograph. The focusing lens was never moved during the making of a pressure photograph with its two comparison exposures in vacuum.

The pressure values for all of the displacements to be given are total pressures, owing to the comparison spectrum being made with the furnace in vacuum. A careful test having shown (see Table II) that the furnace in vacuum and at atmospheric pressure shows a displacement of the lines proportional to that for higher pressures, the shifts may be compared with those for the same difference of pressure with the arc, which was usually operated at atmospheric pressure for the comparison spectrum.

IRON

In Table I the displacements are given in Ångström units for a number of iron lines in the blue region. These are all reversed by the furnace and were as a rule very favorable for close measurement. The furnace spectra at 8, 16, and 24 atmospheres are the regular reversed emission lines. At 12 atmospheres, one plate in absorption was measured and also one in which the iron lines were narrow and unreversed in a photograph of the titanium spectrum. The last column gives the displacements found by Gale and Adams for the arc with 8 atmospheres difference in pressure. The wave-lengths are on the Rowland scale.

It is seen from Table I that the displacements of all the lines, with the exception of those marked *, are of the same order of magnitude for the furnace at any given pressure. The mean shift per atmosphere for these eight lines is also nearly the same except for the two plates at 12 atmospheres, where the rather wide absorption lines of the one and the unreversed lines of the other made measurements difficult.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

TABLE I

PRESSURE DISPLACEMENTS FOR IRON

λ 4250–λ 4462

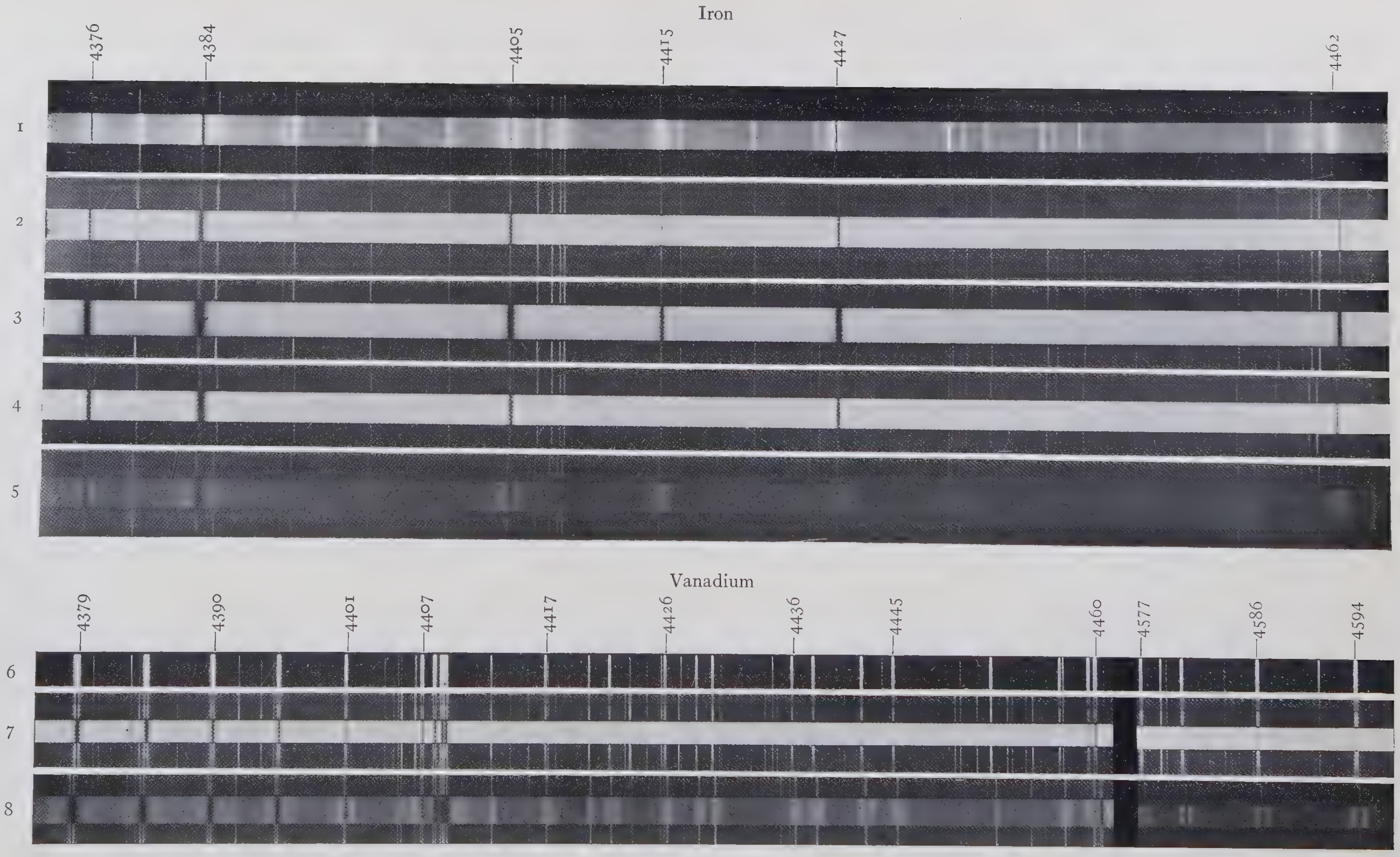
λ	8 Atm. 4 Plates	12 Atm. (Absorption) 1 Plate	12 Atm. (Unreversed) 1 Plate	16 Atm. 2 Plates	24 Atm. 1 Plate	8 Atm. Arc
4250.945.........	0.037	0.062	.....	0.073	0.116	0.022
4271.934.........	0.039	0.054	0.053	0.074	0.102	0.022
4294.301.........	0.036	0.064	.....	0.076	0.113	0.030
4308.081.........	0.040	0.055	0.055	0.081	0.116	0.021
4325.939.........	0.038	0.065	0.053	0.080	0.121	0.020
*4376.107.........	0.020	0.028	0.029	0.039	0.052	0.018
4383.720.........	0.040	0.063	0.056	0.080	0.119	0.027
4404.927.........	0.041	0.059	0.060	0.078	0.121	0.021
4415.293.........	0.040	0.064	.....	0.072	0.115	0.018
*4427.482.........	0.019	0.029	0.028	0.038	0.044	0.017
*4461.818.........	0.018	0.026	0.026	0.034	0.051	0.015
SUMMARY, OMITTING * LINES						
Mean displacement	0.0389	0.0607	0.0554	0.0768	0.1154	0.0226
Displacement per atmosphere.......	0.00486	0.00506	0.00462	0.00480	0.00481	0.00282

Mean furnace displacement per atmosphere 0.00483
Ratio, Arc : Furnace = 282 : 483 = 0.584

The lines λλ 4376, 4427, and 4462 are obviously in a different class as regards displacement, their shifts being about half as large as for the other lines in the list. Other lines in this region show a shift about twice as large as the unstarred lines in Table I, λ 4260.640 being the strongest of this class; but they do not reverse in the furnace and are usually so hazy for pressures above 8 atmospheres that measurements on them are of low weight and they are therefore not included in the present list.

A comparison of the furnace and arc shifts may be made most directly by means of the first and last columns of displacements. It is seen that the furnace displacements are uniformly larger than those of the arc, but that the ratio for individual lines is by no means constant. The largest deviations are for λ 4294 and for the three lines above mentioned which have small furnace displace-

PLATE XIII


Iron

Vanadium

Effect of Pressure upon Electric Furnace Spectra

1. 8 atmospheres 3. 12 atmospheres (absorption) 5. 24 atmospheres 7. 8 atmospheres

ments. The reality of this difference is not altogether certain. These four lines are given at low temperatures and so are relatively strong and well reversed in the furnace spectrum. In the arc they reverse with difficulty, if at all, so that the matter hinges on whether a definitive comparison can be made between a reversed and an unreversed line when the displacement is small and is attended by photographic differences owing to the spectra being photographed on different plates. Duffield,[1] who investigated the iron lines in this region for pressures from 5 to 100 atmospheres, obtained very irregular displacements for the three starred lines of Table I, but they have in general decidedly smaller shifts than the other lines in this table. λ 4294 was also found by Duffield to show variable shifts at different pressures, but usually gave values close to those found by him for the unstarred lines of Table I. The measurements of Humphreys[2] for 41 atmospheres, a pressure which in some respects should be more favorable for lines of this type, give a close relative agreement with the furnace displacements, λ 4294 having a shift of the same order as those measured by Humphreys for the unstarred lines of Table I, while λλ 4376, 4427, and 4462 have a mean shift per atmosphere of 0.00122, the mean value given by the furnace for 8, 16, and 24 atmospheres being 0.00225. Thus, if we allow for the character of the lines in the two sources, the lack of agreement in the measured displacements for furnace and arc may not be great enough to indicate a real relative difference.

Plate XIII reproduces the iron spectrum from λ 4376 to λ 4462, showing two spectra at 8 atmospheres having different intensities for the continuous ground, an absorption spectrum at 12 atmospheres and emission spectra at 16 and 24 atmospheres. The relatively small displacements of the starred lines of Table I may readily be seen.

A large number of photographs have been taken for the region λ 5300 to λ 5500, as the strong lines in this region are especially favorable for examining the characteristics of furnace displacements. Eight lines occur in this region which are of about equal intensity and show pressure displacements of nearly the same magnitude.

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[1] *Philosophical Transactions*, A **208**, 111, 1908.

[2] *Astrophysical Journal*, **26**, 18, 1907.

They reverse readily in the furnace at moderate temperatures, the width of reversal increasing progressively toward the violet. This group of lines has been studied at successive steps of 4 atmospheres up to 24 atmospheres, and also for the possible effect upon displacement of variations in temperature and other conditions of the furnace. The displacement values for various pressures are given in Table II.

Table II shows a maximum variation in the shift per atmosphere of less than 10 per cent for those conditions which may be regarded as standard, namely emission spectra in air at pressures of 4, 8, 16, and 24 atmospheres. The large values given by one plate for 12 atmospheres in absorption are of doubtful weight, owing to the width of the lines. Absorption spectra at 8 and 16 atmospheres with fairly narrow lines gave displacements close to the general mean. The large shifts measured for two plates in carbon dioxide at 8 atmospheres may be real and will be considered later in the discussion. The number and quality of the plates at disposal leave little question that there is a regular increase of displacement with pressure through this range of moderate pressures. The material thus supplements the data from arc investigations, in which as a rule many irregular values have appeared at pressures under 20 atmospheres, and in which the proportionality of displacement to pressure in this range was somewhat doubtful.

The measurements for one atmosphere require explanation, since the probable error is large in proportion to the displacement measured. The furnace was operated in a partial vacuum for the comparison and then at about atmospheric pressure, the interval being regulated by a mercury manometer for which the difference in level was kept equal to the barometric height. Three good plates having narrowly reversed lines were measured in each direction. Single determinations ranged from 0.002 to 0.008, the extreme limits being rare. As the eight lines show displacements of the same magnitude, each plate thus furnished 16 determinations of the interval in question, giving a total of 48 measurements to make up the final mean of 0.00525 for a pressure of one atmosphere. It is believed that fairly high weight can be given this value of the shift for this difference in pressure. It shows that the displace-

TABLE II

PRESSURE DISPLACEMENTS FOR IRON

λ 5328–λ 5456

λ	1 Atm. 3 Plates	4 Atm. 3 Plates	8 Atm. 3 Plates	8 Atm. (CO₂) 2 Plates	8 Atm. (Absorption) 1 Plate	12 Atm. 2 Plates	12 Atm. (Absorption) 1 Plate	16 Atm. 2 Plates	16 Atm. (Absorption) 1 Plate	20 Atm. 2 Plates	24 Atm. 2 Plates	8 Atm. Arc
5328.236..........	0.006	0.021	0.043	0.047	0.044	.....	.....	0.080	.....	0.097	0.124	0.029
5371.734..........	0.006	0.020	0.041	0.045	0.039	0.058	.....	0.079	0.091	0.109	0.121	0.029
5397.344..........	0.005	0.021	0.042	0.047	0.042	0.065	0.068	0.080	0.087	0.107	0.137	0.029
5405.989..........	0.006	0.022	0.041	0.043	0.035	0.059	0.069	0.075	0.080	0.094	0.102	0.027
5429.911..........	0.005	0.021	0.044	0.049	0.044	0.064	0.076	0.083	0.089	0.104	0.126	0.029
5434.740..........	0.004	0.019	0.036	0.042	0.036	0.053	0.070	0.074	0.073	0.093	0.115	0.027
5447.130..........	0.005	0.023	0.047	0.050	0.047	0.063	0.069	0.074	0.081	0.106	0.124	0.031
5455.834..........	0.005	0.020	0.040	0.042	0.039	0.058	0.066	0.071	0.079	0.099	0.106	0.028
Mean displacement	0.00525	0.0210	0.0418	0.0456	0.0407	0.0600	0.0697	0.0770	0.0829	0.101	0.122	0.0286
Displacement per atmosphere.......	0.00525	0.00525	0.00522	0.00570	0.00509	0.00500	0.00581	0.00481	0.00518	0.00505	0.00508	0.00357

Mean furnace displacement per atmosphere, 0.00522

Ratio, Arc:Furnace = 357:522 = 0.684

ments produced by any pressure as referred to the furnace in vacuum may be fairly compared with arc measurements, for which the pressure is usually taken as the excess above one atmosphere.

The arc displacements for 8 atmospheres as measured by Gale and Adams are given in the last column of Table II. There is a close agreement among the individual values as for the furnace. The difference between the mean shifts per atmosphere for the two sources is not so large as for the lines given in Table I, but the different appearance of the lines in arc and furnace for this region makes them more difficult to compare with accuracy. The lines of Table II are usually unreversed in the arc at moderate pressures, only λ 5328 and λ 5371 sometimes showing slight reversal. In the furnace the fact that they are low-temperature lines and are given by the vapor near the ends of the tube permits them to be clearly reversed. Another set of pressure-arc measurements for the lines of Table II is given by Humphreys.[1] His measurements for the eight lines under a pressure of 41 atmospheres gave a mean shift per atmosphere of 0.0023, or less than one-half of the mean furnace displacement. If we take the mean of Gale and Adams' and of Humphreys' values for the shift per atmosphere in the arc, it comes out 0.00293, giving a ratio of arc to furnace displacements of 0.561.

The strong lines $\lambda\lambda$ 5497.735, 5501.683, and 5507.000, are usually unreversed in the furnace, and were not so favorable for accurate measurement as the lines given in Table II. Such measures as have been made indicate that the displacements are of the same order of magnitude as those recorded for the neighboring lines.

Plate XIV reproduces the lines of Table II, with the exception of λ 5328. Variations of the pressure effect are shown ranging from the slight lack of continuity at one atmosphere as compared to vacuum to the large displacements at 24 atmospheres. In all of them, the progressively increasing width of the reversal toward the violet is evident. For 8 atmospheres, both emission and absorption spectra are shown. For 16 atmospheres, two emission spectra with quite different degrees of reversal and an absorption spectrum are given. The spectrum reproduced for 24 atmospheres

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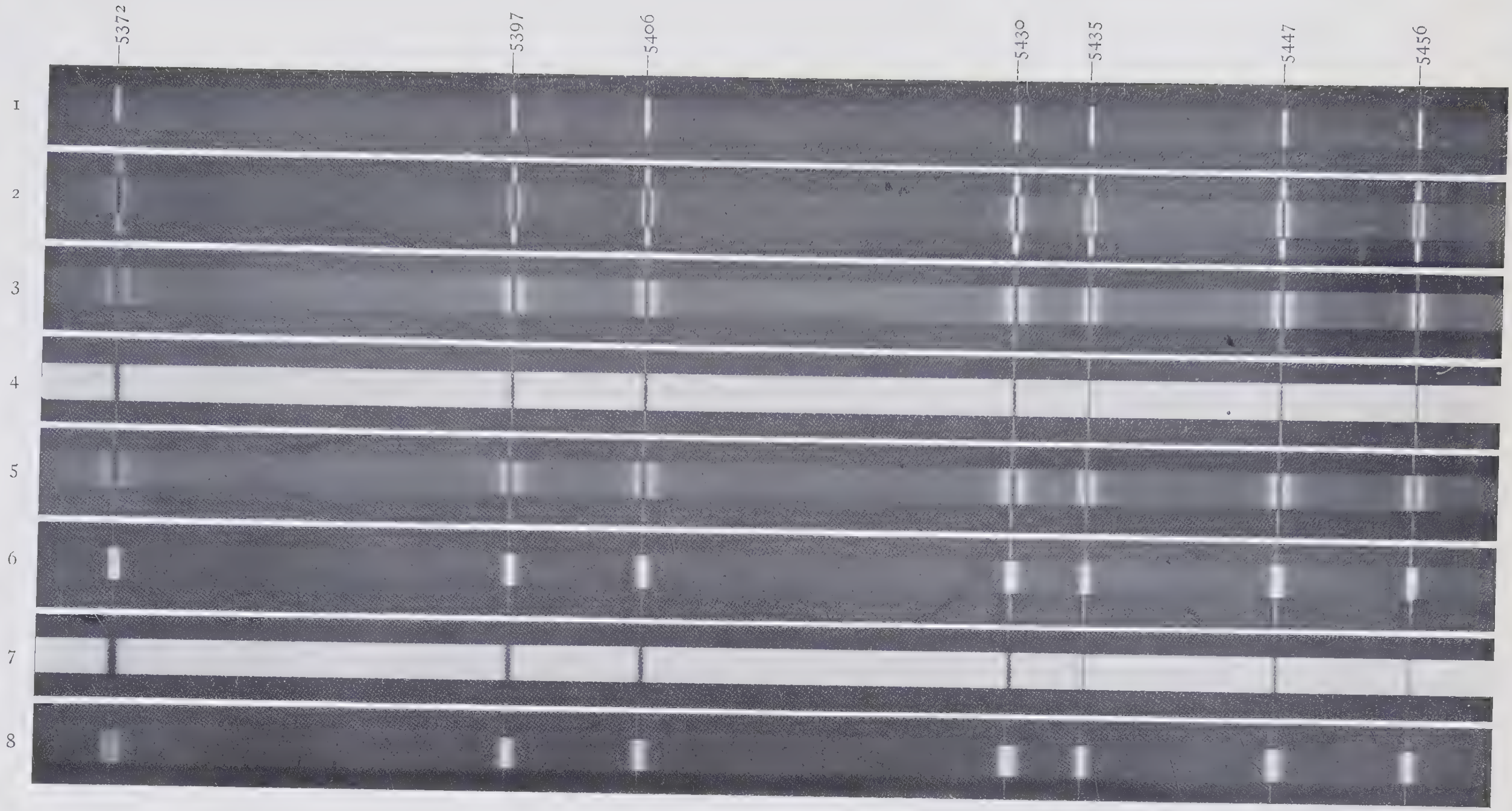
[1] *Loc. cit.*

PLATE XIV



Effect of Pressure upon the Electric Furnace Spectrum of Iron

1. 1 atmosphere
2. 4 atmospheres
3. 8 atmospheres
4. 8 atmospheres (absorption)
5. 16 atmospheres
6. 16 atmospheres
7. 16 atmospheres (absorption)
8. 24 atmospheres

shows for most of the lines only the beginning of reversal. Another plate was obtained at this pressure with rather wide reversals.

TITANIUM

The titanium furnace spectrum was photographed for the region λ 4200 to λ 4600, in which two groups aggregating 20 lines were strong enough to measure up to 16 atmospheres. These lines are not reversed by the furnace at the temperatures employed. A good agreement appeared for sets of measurements by different observers, although the lines were not as satisfactory for measurement as if they had been reversed. An absorption spectrum at 8 atmospheres gave displacements agreeing closely with the values for emission spectra. The measurements are presented in Table III, the arc displacements found by Gale and Adams for 8 atmospheres being given in the last column. The mean furnace shift per atmosphere is weighted on account of the small number of values for 12 atmospheres.

Considering the character of the lines there is a good agreement between the displacements at 8 atmospheres for emission and absorption and also between the shifts per atmosphere at 8 and 16 atmospheres. The ratio of mean arc and furnace displacements is almost the same as for the iron lines of Table I. The arc displacements for the 11 lines beginning with 4512.906 are consistently somewhat higher than for the first 9 lines in the list, while the furnace displacements are of the same magnitude throughout.

As in the case of the iron spectrum, only the best lines are measured in this region. A much larger number can be obtained with varying degrees of accuracy, the precision in most cases becoming much less at higher pressures.

VANADIUM

Recent work by Rossi[1] has furnished measurements for the displacements of the stronger vanadium lines from λ 4000 to λ 4600 as given by the arc at pressures of 15, 30, 50 and 100 atmospheres. The writer has taken a series of ten furnace plates for the same region at pressures of 8 and 16 atmospheres. Compressed air was used, with metallic vanadium in the furnace tube. On the better photographs the lines were in almost all cases reversed, the comparison lines also being frequently reversed, so that close measurements were possible.

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[1] *Astrophysical Journal*, **34**, 21, 1911.

TABLE III

Pressure Displacements for Titanium

λ	8 Atm. 2 Plates	8 Atm. (Absorption) 1 Plate	12 Atm. 1 Plate	16 Atm. 2 Plates	8 Atm. Arc
4286.168....	0.045	0.049	.....	0.087	0.021
4287.566....	0.040	0.048	.....	0.099	0.024
4289.237....	0.050	0.049	.....	0.075	0.025
4291.114....	0.049	0.042	.....	0.091	0.022
4295.914....	0.046	0.054	.....	0.094	0.022
4298.828....	0.045	0.054	.....	0.095	0.025
4300.732....	0.046	0.046	0.081	0.099	0.021
4301.158....	0.048	0.050	0.076	0.088	0.024
4306.078....	0.044	0.048	0.073	0.091	0.024
4512.906....	0.047	0.043	.....	0.088	0.029
4518.198....	0.046	0.049	.....	0.099	0.029
4522.974....	0.047	0.045	.....	0.099	0.031
4527.490....	0.044	0.056	.....	0.100	0.029
4533.419....	0.043	0.047	0.077	0.097	0.031
4534.953....	0.047	0.052	0.074	0.094	0.034
4535.741....	0.043	0.046	0.082	0.102	0.029
4544.864....	0.048	0.050	.....	0.094	0.031
4548.938....	0.045	0.044	.....	0.099	0.031
4552.632....	0.045	0.046	.....	0.097	0.029
4555.662....	0.046	0.049	.....	0.090	0.029
Mean displacement..	0.0457	0.0483	0.0772	0.0939	0.0270
Displacement per atmosphere......	0.00571	0.00604	0.00643	0.00587	0.00338

Mean furnace displacement per atmosphere, 0.00592

Ratio, Arc : Furnace=338 : 592=0.571

Table IV gives the furnace displacements for vanadium, the arc displacements measured by Rossi for 15 atmospheres being given in the last column. The values in the third column, for unreversed lines at 8 atmospheres, were obtained from a plate made for the iron spectrum, but containing the stronger vanadium lines narrow and bright from impurities in the iron.

From Table IV it is seen that the displacements per atmosphere at 8 and 16 atmospheres agree within 10 per cent. As the reversals at 16 atmospheres are rather wide, a difference of this magnitude may fairly be ascribed to errors of measurement and the propor-

TABLE IV

Pressure Displacements for Vanadium

λ	8 Atm.	8 Atm. (Unreversed)	16 Atm.	15 Atm. Arc
4090.728....	0.070	.....	.....	0.071
4092.821....	0.040	.....	.....	.....
4095.633....	0.045	.....	.....	0.061
4099.941....	0.040	.....	.....	0.049
4102.321....	0.060	.....	.....	0.047
4105.318....	0.047	.....	.....	.....
4109.905....	0.040	.....	.....	0.052
4111.940....	0.046	.....	.....	0.043
4115.330....	0.038	.....	.....	0.043
4116.634....	0.053	.....	.....	0.042
4123.539....	0.040	.....	.....	0.050
4128.251....	0.047	.....	.....	0.046
4132.100....	0.043	.....	.....	0.049
4134.589....	0.046	.....	.....	0.044
*4179.542....	0.016	.....	.....	.....
4182.755....	0.041	.....	.....	.....
*4330.189....	0.023	.....	0.039	0.042
*4332.988....	0.018	.....	0.034	0.041
*4341.167....	0.020	.....	0.045	0.052
*4353.040....	0.023	.....	0.039	0.040
4379.396....	0.042	0.049	0.086	0.046
4384.873....	0.042	0.040	0.087	0.046
4390.149....	0.048	0.044	0.085	0.043
4395.413....	0.040	0.046	0.084	0.047
4400.738....	0.035	0.044	0.091	0.047
4406.810....	0.037	0.042	0.081	.....
4407.810....	0.040	0.047	0.078	.....
4408.364....	0.040	0.040	.....	.....
4408.683....	0.057	0.047	.....	.....
4416.636....	0.035	0.042	0.084	0.043
4421.733....	0.044	0.037	0.096	0.046
4426.201....	0.044	.....	0.075	0.044
4428.711....	0.034	.....	0.065	0.046
4429.958....	0.044	.....	.....	0.047
4436.313....	0.034	.....	0.062	0.049
4438.006....	0.035	0.031	0.077	0.043
4441.881....	0.033	0.036	0.084	0.050
4444.566....	0.035	0.037	0.074	0.049
4457.600....	0.038	.....	0.054	.....
4459.922....	0.036	0.033	0.059	.....
4460.389....	0.041	0.035	0.080	.....
*4577.356....	0.019	.....	0.038	0.044
*4580.590....	0.018	.....	0.034	0.042
*4586.552....	0.020	.....	0.033	.....
*4594.297....	0.021	.....	0.036	0.041

Summary, Omitting * Lines

Mean displacement.....	0.0427	0.0406	0.0779	0.0478
Displacement per atmosphere......	0.00534	0.00507	0.00487	0.00319

TABLE IV—*Continued*

λ	8 Atm.	8 Atm. (Unreversed)	16 Atm.	15 Atm. Arc
Mean displacement of lines also in arc..	0.0428	0.0406	0.0808	......
Displacement per atmosphere of lines also in arc........	0.00535	0.00507	0.00505	......

Mean furnace displacement per atmosphere, 0.00509
Mean furnace displacement per atmosphere for lines also in arc, 0.00516
Ratio, Arc : Furnace=319 : 516=0.618

tional increase of the displacements in general is in harmony with the results for iron and titanium.

The ratio of the mean displacements per atmosphere for lines common to the furnace list and to Rossi's list for the arc is close to that found in Tables I and III. The last two columns of Table IV show the relative displacements in furnace and arc for nearly equal pressures. Nine furnace lines which have shifts much smaller than the average are starred and are not included in the averages at the end of the table. For the seven lines of this set which were measured by Rossi, there appears to be a distinct relative difference as compared to the unstarred lines. At 16 atmospheres the furnace displacements of the starred lines are close to those of the arc for 15 atmospheres while the displacements for the other lines approach a 2 : 1 ratio. These lines were measured on several good furnace plates and there can be no doubt of their large difference from the unstarred lines. So far as can be judged from the reproductions of Rossi's spectra, the starred lines in the arc spectra are comparable in quality with the others in his table. It is to be noted, however, that Rossi's measurements for 30 atmospheres, which gave the lines distinctly reversed in the arc, show consistently smaller values for the starred lines than for the others. Until a more direct comparison of furnace and arc photographs is possible, there is some question as to the certainty of a large relative difference for these lines.

Vanadium spectra at 8 and 16 atmospheres, accompanied by an arc spectrum taken at atmospheric pressure, are reproduced in Plate XIII. The four lines from λ 4577 to λ 4594 appear at the right, showing their displacements relative to those of the lines near λ 4400. The two parts of the spectrum at 8 atmospheres were enlarged from the same negative, so that photographic differences are eliminated.

EFFECT UPON DISPLACEMENT OF VARIATION IN FURNACE CONDITIONS

Since many modifications are possible in the arrangement and operation of the furnace, it seemed worth while to see what differences, if any, changes in certain variables might make in the pressure displacements. The region of spectrum selected for these experiments consists of the iron lines whose measurements for different pressures are given in Table II, with the addition of λ 5269.723 on some of the photographs. The lines of this group have the advantages of giving fairly large displacements, all of the same order of magnitude, so that the mean can be used to determine the effect of any special condition, and of appearing usually in reversal, which in the case of low temperature lines greatly increases the accuracy of measurement. The various modifications tried will be considered in turn.

1. *Temperature difference.*—A variation in pressure displacement inversely as the absolute temperature of the source would be of the proper order of magnitude to account for the difference observed in furnace and arc displacements. It has been possible to test this point with the furnace in such a way that a relation of this kind should have shown itself, but the results have failed to reveal a dependence of displacement upon temperature.

In these experiments a definitive test required a pressure high enough to give a large displacement and also a temperature difference as great as possible, both conditions acting against obtaining lines of the best quality for a close comparison. Pressures of 12, 16, and 20 atmospheres were used. At each pressure, a temperature was taken as low as would give clearly defined lines and then as high as could be employed. It was not possible to go to the upper limit of the furnace temperature, as wide reversals were given, and if the exposures were made long enough to narrow the reversals only temperatures up to a certain limit could be used without generating large quantities of white vapor which cut off the light.

Little confidence could be placed in comparative measurements for the extreme low and high temperatures on account of the diffuseness of the lines at the pressures employed. To obtain good lines for measurement, the furnace was always operated at moderate temperatures (not above 2400° C.). The method adopted for the temperature comparison was to make exposures at the same pressure for low and high temperatures on the same plate, placing one outside of the other by means of the occulting device above the slit, and making vacuum exposures before and after to test for instrumental disturbance during the experiment.

Twelve plates were taken by this method for the iron lines from λ 5300–λ 5500 and from λ 4200–λ 4500. Various temperature intervals were taken, usually those for which the pyrometer gave differences of about 500° C. The actual difference was probably greater than this on account of the readings being affected by the cloudy condition of the furnace interior at the high temperatures. Very good plates were obtained at 12 atmospheres with lines reversed in each photograph taken with a temperature difference of about 300° C. The reversals appeared to be perfectly continuous in the two spectra side by side. Larger temperature intervals gave the low temperature lines unreversed, and the maximum difference should have been given for 20 atmospheres with a temperature interval of at least 500°. This gave an absolute displacement of about 0.1 Å for both lines, and no difference in position could be detected between bright low temperature lines and the same lines reversed at high temperature. A difference in displacement inversely proportional to the absolute temperature would amount to about 20 per cent under these conditions and although the quality of the lines makes one hesitate to say that there is certainly no difference, it can be said that a difference of this magnitude should have been perceptible in a visual comparison made in this way. Higher pressures were tried, up to 30 atmospheres, but difficulties attendant on the increased pressure prevented the obtaining of photographs satisfactory for comparison at both high and low temperatures.

Evidence offered by the structure of reversed lines bears on the effect of temperature difference. All of the lines whose measurements are given in this paper, when reversed at all, show reversals nearly if not quite symmetrical up to the highest pressures observed, 24 atmospheres in the case of the iron lines. An increased displacement for the low temperature line given by the cooler parts of the furnace tube should make the line as a whole unsymmetrically reversed, the portion to the violet of the absorption line being the wider. Lines having this appearance are rare in any source, the arc usually giving strong widening to the red when lines reverse unsymmetrically, while, for the lines considered in this paper, the symmetry of the arc reversals agrees with those shown by the furnace. A condition which is conceivable but highly improbable may be mentioned. If the emission line widened under pressure unsymmetrically toward the red and if at the same time the absorption line had a larger displacement owing to the lower temperature of the vapor producing it, the widening of the emission line and the increased displacement of the absorption line might keep pace and preserve the appearance of symmetrical reversal. There is no reason to believe that this actually takes place. Such lines when unreversed under pressure should show strong widening toward the red. The iron lines of Table II have been obtained in the furnace unreversed at several pressures. They also appear usually unreversed in the arc under pressure and much widened when iron terminals are used, but this widening remains nearly symmetrical both in furnace and arc.

If a decrease of displacement with increasing temperature were found really to exist, the widening of the lines, which seems to accompany increased pressure in all sources which have been observed, would be expected to remain, and we should have the condition in solar and stellar spectra that lines widened but not distinctly displaced might indicate high pressures which produced little or no displacement by reason of the high celestial temperatures involved. The evidence presented by the furnace experiments, however, is against a dependence of the pressure displacement on the temperature of the source.

2. *Effect of different compressed gases.*—It was noted in the dis-

cussion of Table II, that two good plates for the furnace in carbon dioxide at 8 atmospheres gave consistently larger displacements than were observed for compressed air, the difference of the means amounting to about 10 per cent. This difference is not certainly beyond possible errors of measurement, but the measurements by different observers agreed very closely and the difference is larger than was obtained between photographs of similar quality for any other conditions of the furnace. Photographs of poorer quality for the iron lines of Table I and the titanium lines of Table III, each at 8 atmospheres in CO_2, failed to show a decided difference from corresponding photographs for air. Higher pressures with carbon dioxide gave poor results on account of the large amount of white oxide which was generated.

The possibility of carbon dioxide giving larger pressure displacements than air on account of its higher dielectric constant was discussed in my preliminary paper.[1] The present results show that this can have no important bearing on the difference between furnace and arc displacements, since the greater part of the furnace work has been done with air. Rossi[2] has recently tested this question for the arc by obtaining the displacements of a number of iron lines in air and in carbon dioxide at 15, 30, and 50 atmospheres. The mean displacements for the two gases agreed closely.

It is worthy of note in this connection that, judging from my experiments with the furnace, the carbon dioxide is probably largely turned to carbon monoxide before it reaches the region where maximum radiation is taking place, and the same is probably true to a certain extent for the arc. As the dielectric constant of carbon monoxide is but slightly greater than that of air, being much less than for carbon dioxide, but little difference in displacement is to be expected through this agency. The furnace should, however, be more sensitive than the arc to any influence which the compressed gas can exert, since such a gas is thoroughly mixed with the metallic vapor and brought to the same temperature.

3. *Low vapor-density.*—Table V gives a summary of the displacements for the furnace at 8 atmospheres under various conditions,

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[1] *Loc. cit.*

[2] *Philosophical Magazine* (6), **21**, 499, 1911.

the furnace tube being used without jacket in order to eliminate any effect due to vapors given off by the jacketing materials in the presence of oxygen. Compressed air was used throughout. On account of the tube rapidly becoming thinner when fully exposed to the air, some difficulty was found in keeping the temperature approximately constant, which affected the clearness of the reversals. The plates were thus not so satisfactory for measurement as those for which the jacket was used, and the deviations of small size from the values given in Table II are probably to be ascribed to this cause. From one to four good plates were measured for each condition summarized in Table V.

TABLE V

PRESSURE DISPLACEMENTS FOR IRON AT 8 ATMOSPHERES UNDER VARYING CONDITIONS OF THE FURNACE

λ	TUBE 20 OR 25 CM LONG				5 OR 6.4 CM TUBE
	From Table II	Small Amount of *Fe*	*Fe* with *Ca* and *NaCl*	Small Amount of *Fe* with *Ca* and *NaCl*	
5269.723....	.....	0.044	0.036	0.038	0.037
5328.236....	0.043	0.043	0.044	0.041	0.039
5371.734....	0.041	0.043	0.040	0.041	0.038
5397.344....	0.042	0.044	0.040	0.045	0.045
5405.989....	0.041	0.043	0.037	0.041	0.039
5429.911....	0.044	0.044	0.040	0.040	0.042
5434.740....	0.036	0.044	0.033	0.037	0.039
5447.130....	0.047	0.042	0.038	0.042	0.038
5455.834....	0.040	0.042	0.035	.....	0.039
Mean.......	0.0418	0.0432	0.0381	0.0406	0.0396

Plates taken without the jacket for the regular size of tubes and usual amount of iron gave means very close to those of Table II; so the first column of displacements is taken directly from Table II and used for comparison with the values for the special conditions in which no jacket was employed.

A very little iron (about 0.05 gram as compared with 2 grams or more generally used) gave lines unreversed, but of good quality for measurement. The displacements for the several lines agreed very closely as is seen in the third column of Table V, the mean being close to the general mean of Table II. The furnace thus confirms the conclusion that has been drawn by a number of observers of the arc under pressure that displacement is not dependent on the quantity of the metallic vapor present.

4. *Effect of foreign vapors.*—In a long column of vapor such as that given by the furnace tube, irregular refraction effects are possible, which may under certain conditions give a displacement of the lines to the red. In the usual operation of the furnace, with the jacket about the tube, the spectrum showed that a considerable amount of calcium and sodium was present, presumably given off by the carborundum and graphite, and in order to see if the displacement was affected thereby, an attempt was made to increase the effect by introducing a large quantity of metallic calcium and sodium chloride with the iron. To insure maximum effect during the pressure exposure, these were put into the tube, by removing the window-holder, after the first comparison exposure in vacuum had been made. A brilliant banded spectrum from the calcium, together with very widely reversed D lines, attested the presence of a dense vapor from these substances, especially in the earlier stages of the furnace run. Some of the photographs under these conditions were rather difficult to measure, the reversals appearing as if an unsteady distribution of the vapor had existed during the exposure, which may have been due to disturbances other than refraction. I am not prepared to say that anomalous dispersion does not enter in some degree when a mixture of this sort is present in the tube, but such effect as there is on the displacements is in the direction of lower values; so that the generally high values of the furnace as compared to the arc are not explained by an influence of this sort. Tubes with 25 cm heated between the contact blocks were used for some of these tests. The mean displacements obtained are given in the fourth and fifth columns of Table V, the latter column giving the results when a very little iron was used with the calcium and salt. The deviation of the means from the value in column two, in view of the character of the lines, is not large enough to indicate a real effect on the displacement.

5. *The use of short tubes.*—The method of using tubes of about one-fourth the regular length was described on p. 186. If the length of the column of vapor were an essential factor in determining the

displacement, a decided difference should have appeared for these tubes. The vapor-density was kept closely comparable with that for the long tubes by using a quantity of iron proportional to the length of the tube. The results are given in the final column of Table V. A difference of only 5 per cent appears between this mean and that in the second column, so that the length of the tube can be regarded as without decided effect on the displacement.

COMPARISON WITH THE ZEEMAN EFFECT

A comparison of the pressure displacements with the separations produced by a magnetic field for the lines considered in the present paper offers little evidence in support of a close connection between the two phenomena.

The magnetic separations for the iron and titanium lines have been published by the writer[1] and those for vanadium by Mr. Babcock.[2]

The iron lines of Table I show triplet separation in the magnetic field with the exception of $\lambda\lambda$ 4251 and 4294 which are complex. The remaining lines, including λ 4415 which may have more than three components, have the following values of the separation divided by the square of the wave-length for a field of 16,000 gausses:

λ	$\Delta\lambda/\lambda^2$	λ	$\Delta\lambda/\lambda^2$
4271.934	1.868	4404.927	1.720
4308.081	1.724	4415.293	1.734
4325.939	1.309	4427.482	2.194
4376.107	2.214	4461.818	2.185
4383.720	1.727		

These measurements for the separations are all of high weight. $\lambda\lambda$ 4376, 4427, and 4462 are seen to have magnetic separations of equal magnitude, this separation being distinctly larger than those of the remaining triplets in the list. Their pressure displacements in the furnace, however, are about half as large as those of the other lines. The relative effects of pressure and of the magnetic field are thus opposite for the two groups of triplets in this list.

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[1] *Papers from the Mount Wilson Solar Observatory*, Vol. II, Pt. 1; *Carnegie Institution Publication* No. 153, 1912.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 55; *Astrophysical Journal*, **34**, 209, 1911.

The iron lines of Table II, which agree among themselves as to pressure displacement, show a variety of magnetic separations, all of them complex with the exception of λ 5434.740, which is unaffected by the magnetic field. There is therefore no clear basis for comparison of the two effects. The case is similar for the titanium lines of Table III, the displacements being of about equal magnitude, while the magnetic separation varies from an unaffected line (λ 4295.914) to those having from 8 to 12 components.

The vanadium lines of Table IV show two groups of four lines each (λ 4330–λ 4353 and λ 4577–λ 4594) which have about half of the average displacement. These 8 lines are all given as showing triplet separation in the magnetic field, as do 25 other lines in Table IV. The average value of $\Delta\lambda/\lambda^2$ for 20,000 gausses is 1.81 for the 8 small-shift lines and 2.55 for the 25 lines having larger displacements. The effects of pressure and of the magnetic field are thus in the same direction for these groups.

The data here given do not materially alter the general situation as to the relation of the pressure and Zeeman effects, since the writer has shown[1] that no close correspondence exists between the effects for individual lines or even small groups, a general agreement as to relative magnitude becoming apparent only when the means of large numbers of lines are considered.

THE RELATION OF DISPLACEMENT TO WAVE-LENGTH

One or two points concerning the iron lines of Tables I and II may be referred to here, though the number of lines is small for a discussion of the relation to the wave-length. The average displacement per atmosphere of the lines from λ 5300 to λ 5500 is but little larger than for the lines showing the larger shifts in the region λ 4200 to λ 4500. The displacements of the three lines in Table I showing small shifts, however, are related to the displacements of the lines in Table II very nearly as the third power of the wave-length, a relation which was found by Gale and Adams[2] to hold for the mean displacements of iron lines in the arc through a long range of the spectrum. The ratio of the cubes of the mean wave-lengths for the two regions would require a displacement of 0.023 Å at 8 atmospheres for λλ 4376, 4427, and 4462, a value slightly higher than that given for these lines in Table I.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 46; *Astrophysical Journal*, **31**, 433, 1910.

[2] *Loc. cit.*

The chief significance of this result, in the writer's opinion, lies in the fact that the three blue lines are very similar to the lines of Table II in their response to temperature excitation of the furnace. At low temperatures they are relatively strong as compared to the other lines in Table I, and the similarity holds for their appearance in the arc, where these low temperature lines are usually sharp and reverse with difficulty. The unstarred lines of Table I are less comparable in general behavior with those of Table II, since they are strong under all conditions and are susceptible to pronounced widening and reversal in the arc. The lack of distinct change in the displacements of such lines with the wave-length seems less significant than the approximate third-power variation for lines showing the same sort of response to temperature.

THE DIFFERENCE OF FURNACE AND ARC DISPLACEMENTS CONSIDERED IN CONNECTION WITH WIDENING PHENOMENA

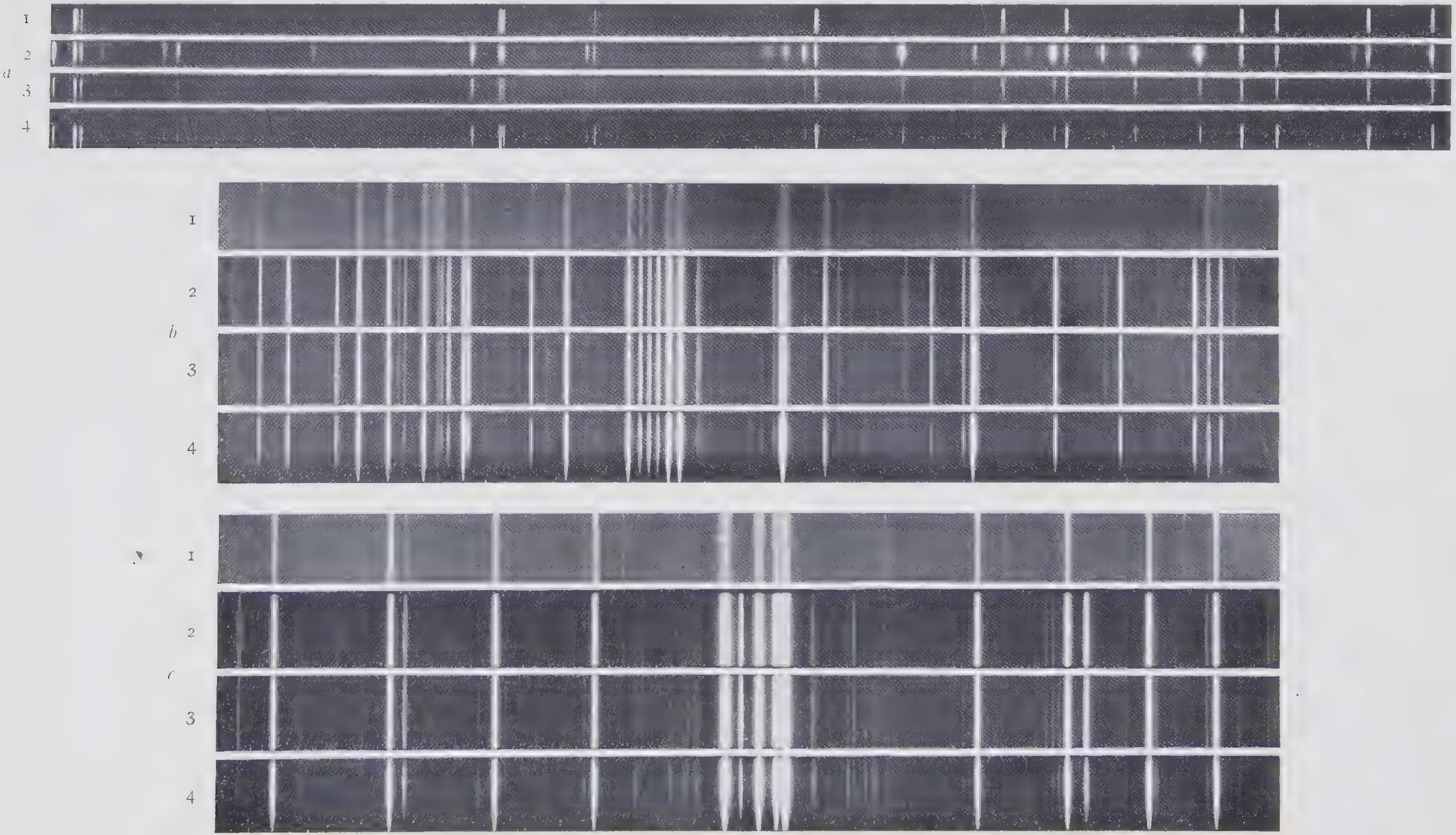
It is apparent in Tables I to IV that there are consistent differences, from 50 to 75 per cent, between the displacements per atmosphere of groups of lines given by the furnace and arc which as a rule are fully comparable as to accuracy of measurement in the two sets of spectra. Naturally there are individual cases, some of which have been noted, where the quality of the lines for measurement is better in one source than in the other, but this can scarcely exert any effect on the general result. The precautions taken to make instrumental conditions as much alike as possible for furnace and arc observations made in this laboratory have been described. As a guard against personal differences in measurement, Miss Lasby, who took part in the reduction of the pressure-arc photographs, has kindly measured several of the furnace plates, with the result that no systematic difference in values can be ascribed to the method of measurement. The possible influence of unsymmetrical widening has been carefully considered, but this appears to explain but little of the effect, largely because most of the lines listed here do not seem to widen unsymmetrically in any source. The reversals have occasionally been obtained very narrow compared to the total width of the line for pressures of 16 atmospheres or more (see for example λ 5371 in No. 6 of Plate XIV). In such cases a widening of the reversal toward the red which could affect the measurement would be accompanied by a very pronounced dissymmetry of the line as a whole.

The various modifications of the furnace which have been tried have proved ineffective in producing a distinct difference in the mean displacement of the lines. For most of the differences between the radiation conditions of furnace and arc, however, it is difficult to bridge fully the gap between the two sources.

It is now desired to call attention to a difference in the structure of furnace and arc lines which I believe may furnish the key to their different displacements. I have always observed in furnace spectra a certain "softness" in the appearance of the lines. As compared to arc lines photographed on the same plate, the furnace lines have a more uniform intensity over their width, so that for the same width in the negative the furnace lines are less dense than those of the arc. This indicates a flatter intensity-curve for the furnace lines, a smoothing down of the central maximum, which seems to be different in character and more fundamental than a widening produced by changes in the quantity of vapor present.

The furnace, except when used for pressure experiments, has generally been operated in a partial vacuum to avoid oxidation, and even this condition, which favors the narrowness of furnace lines as compared to those given by the arc in open air, showed this relatively large width of lines in the furnace spectrum. In order to make a closer comparison of the widening in furnace and arc, a special set of photographs was made for the iron and titanium lines whose pressure displacements are studied in this paper. The furnace spectrum was photographed at atmospheric pressure, the outlet valve being left open. Then a number of exposures were made on the same plate with the arc in open air for currents ranging from 2 to 20 amperes, the exposure times being graduated to make the various arc spectra of about equal intensity. A

PLATE XV



Furnace and Arc Spectra of Iron and Titanium

a Iron λ 5270 to λ 5456. *b*. Titanium λ 4281 to λ 4327. *c*. Titanium λ 4513 to λ 4556

change in current seems to be the most effective means of increasing the widening of arc lines when plenty of the substance is ready to be vaporized, as when metallic terminals are used. As we cannot get at the relative quantity of vapor per unit volume in the furnace and arc under given conditions, the two sources are best made comparable by having the metal abundant in each, as was done by placing a large amount of powdered iron or titanium in the furnace tube and using as arc terminals iron rods or carbons, of which the lower held a large quantity of titanium carbide.

Plate XV shows portions of the iron and titanium spectrum containing the lines of Tables II and III as given by the furnace at atmospheric pressure and by the arc in air at 20, 10, and 2 amperes. Width of slit and all adjustments of the spectrograph were unchanged during each series and the negative was copied on a single plate, effects of this sort being very sensitive to differences in photographic contrast. The first set of spectra shows the iron arc at 20 amperes giving about the same degree of reversal as the furnace, λλ 5269, 5328, and 5371 being reversed. None of the lines are reversed in the arc at 10 amperes or less. It is seen that the furnace lines are wider than those of the arc even for 20 amperes, while the negative shows the arc lines to be slightly the blacker. Another negative, not so favorable for reproduction, shows a furnace spectrum having lines of the same width as arc lines which are twice as black.

The lower part of Plate XV shows the two portions of the titanium spectrum measured in Table III. The enlargements are made from the same negative, the furnace spectrum at atmospheric pressure, together with arc spectra at 20, 10, and 2 amperes, being arranged as for the iron series above. Several of the stronger lines show the beginnings of reversal in the furnace, such lines being distinctly reversed in the arc at 20 amperes, but not for 10 amperes. The greater width of the furnace lines in proportion to their density when compared to the arc lines is very distinct. The appearance of the furnace lines is approached most nearly by the arc at 20 amperes, but even then the widening conditions in the arc are not as strong as in the furnace.

The furnace was not used at atmospheric pressure for vanadium, but the difference in structure of furnace and arc lines is shown by comparing the arc spectrum of vanadium in Plate XIII with the vacuum furnace photograph immediately below it, used as comparison for that at 8 atmospheres pressure, arc and furnace exposures being on the same plate. Even in vacuum, the furnace gives broad lines, easily reversed, in contrast to the narrow, dense structure of the corresponding lines in the arc.

It would seem, therefore, that we have consistent experimental evidence of a tendency of the furnace to produce lines wider in proportion to their density than are given by the arc, at least for the moderate currents usually employed in pressure-arc work. The application to the displacement question is that *if the radiation of the furnace is such as to give lines which are wide in proportion to their density, then since widening and displacement are inseparably bound together when pressure is acting, the furnace lines, being more susceptible to the widening influence, should also respond more readily to the displacing action of pressure.* Again it must be borne in mind that this widening refers to a change in the intensity-curve for a given line, not to the general strengthening and proportional widening which results from greater vapor-density.

It is not clear why the radiation conditions of the furnace should give lines of large absolute width, and the theory of widening, so far as worked out, gives little aid in the explanation; but experiment shows the action of the furnace to be in this direction. It is evident, however, that the conditions of emission and absorption in the furnace tube will account for some features in the appearance of the lines. Reversal certainly takes place easily in the furnace for most of the lines considered in this paper. It follows that such lines when unreversed will have the peak of the emission-curve flattened to a greater or less extent by absorption. An approach to uniform density across the width of the furnace line would then result, especially as there is some variation in the condition of the vapor during the exposure time required for these large scale photographs. This relation of emission and absorption, together with a width of line approached in the arc only for high current-strength, form the distinguishing characteristics of the furnace lines.

It seems to me probable that such other apparent variations of pressure displacement in different sources as have been observed may well be based on this ability of a source to give widened lines when such widening depends upon features of the source other than vapor-density. Gale and Adams[1] obtained consistently larger mean displacements for a number of lines in the titanium spark than were given by the arc. We have again the experimental fact that lines are wider in the spark than in the arc. Gale and Adams also note that these titanium lines reverse more widely in the spark, though usually symmetrically. The decidedly larger displacements of enhanced lines given by the spark may be based on the same cause, since for such lines the widening influence of the spark discharge has a maximum effect.

The mechanism by which the furnace gives relatively wide lines must be quite different from that acting in the spark, where the widening depends upon the disruptiveness of the discharge and the lines can be made very narrow by the use of self-induction in the circuit.

According to the above hypothesis, any light-source whose radiation is such as to give widened lines should give relatively large pressure displacements. A very high-current arc should give larger displacements than an arc with low current. Also, it should be possible to vary spark displacements by gradually taking out self-induction and increasing the capacity. No systematic experiments on these points have been carried out, and in any case comparative measurements would be difficult by reason of the large difference in the character of the lines produced by very diverse conditions of the same source. For sources widely different in nature, as are the arc and the furnace, differences in radiation can exert their full effect and still lines can be obtained in the spectrum of each whose measurements are fully comparable.

SUMMARY

The leading results of this investigation are as follows:

1. Sufficient material has been collected to give measurements of fairly high weight for the displacements of certain groups of lines in the iron, titanium, and vanadium spectra.

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[1] *Op. cit.*, p. 41.

2. The measured displacements of iron lines for pressures from 1 to 24 atmospheres and for titanium and vanadium lines for 8 and 16 atmospheres as compared to vacuum show a close proportionality between displacement and pressure for these ranges.

3. The pressure effect in absorption has been developed as a useful method for certain kinds of lines, giving displacements in general of the same magnitude as for emission lines.

4. Temperature differences of at least 500° C. for a pressure of 20 atmospheres have failed to show a definite variation of displacement with the temperature.

5. Variations in quantity of vapor present and in length of tube, also the addition of foreign vapors, have not appeared to affect the furnace displacements.

6. Some additional data have been secured regarding the degree of correspondence between displacement and magnetic separation.

7. A few iron lines affected similarly by temperature-changes are compared in regard to change of displacement with wave-length.

8. The furnace has in general given displacements much larger than those of the arc, and a special study has been made of the structure of furnace and arc lines which it is believed may contribute to an explanation of this difference.

I am indebted to Miss Sheldon for regular assistance in measuring the photographs, also to Miss Lasby for check measurements on several plates.

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TERTIARY STANDARDS WITH THE PLANE GRATING THE TESTING AND SELECTION OF STANDARDS

FIRST PAPER

By CHARLES E. ST. JOHN and L. W. WARE

INTRODUCTION

At the meeting, on Mount Wilson August–September 1910, of the International Union for Co-operation in Solar Research, the question arose as to the adaptability of the plane-grating spectrograph of long focus to interpolating between the secondary standards in the determinations of the standards of the third order, and in the measurement of arc, spark, and solar spectra in the international units. In the recommendations of the Committee on Wave-Lengths that were adopted by the Conference occur the following resolutions:[1]

> 4. The laboratories or observatories possessing first-rate concave gratings are invited to determine by interpolation as soon as possible standards of the third order in the spectrum of the iron arc within the above range of spectrum [i.e., λ 4282–λ 6494].
>
> 8. It is very desirable that in different laboratories possessing concave gratings of the best quality, photographs of arc, spark, and solar spectra, and new measurements according to the international system, shall be taken as soon as possible.

This preference of the concave grating over the plane grating was questioned by those who have had experience in the determinations of wave-lengths by means of the plane-grating spectrograph of long focus. The question was raised by Professor Plaskett, and in response the position of the Committee was given by Professor Kayser, who said:[2]

> I think it will be much more difficult to use plane gratings, because the spectrum is not normal and it is necessary to apply corrections. I have no plane gratings of my own and have never tried to measure wave-lengths with

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[1] *Transactions of the International Union for Co-operation in Solar Research*, **3**, 33.

[2] *Ibid.*, p. 42.

them, so I cannot tell if the order of precision is the same as for concave gratings, but in every case I should prefer concave gratings.

The discussion was later taken up by Newall, Adams, Fabry, and St. John,[1] and the point of view of those who have had experience was expressed by Newall, who said:

> Many of those who are engaged in solar observations are using plane gratings, arranged in the Littrow form, and many of us are of the opinion, rightly or wrongly, that the plane grating can compete quite well with the concave grating, provided the rest of the optical train is accurate enough. So it is hoped that provisionally we may regard the words "concave grating of the first quality" as not to be taken as of the essence of that resolution.

As is well known, considerable use of the plane grating is made at the observatory on Mount Wilson for determining the wave-length of spectral lines; and it is exceedingly important to know what degree of precision can be obtained by the use of the plane grating as compared with the concave grating in interpolating between standards about 50 Ångströms apart, when the former is employed in a spectrograph of great focal length.

The immediate motive for taking up the determination of the wave-lengths of the tertiary standards in the red arose from the need of standards for determining the wave-lengths of the oxygen band in the solar spectrum at about λ 6300. The original intention was to use the wave-lengths of the tertiary standards published by Professor Kayser,[2] but when these were tried it was at once found that they did not form a consistent series on Mount Wilson. If these tertiary standards were omitted, however, the secondary standards did form a consistent series, provided the international values for the wave-lengths were employed, instead of the "adjusted" values of Kayser. This induced us to redetermine the wave-lengths of some of the tertiary standards in this region, with what at first were surprising results. For this purpose we used the international standards of the second order. The results from a preliminary series of determinations are shown in Table I, together with the international standards and the corresponding data from Kayser's table of wave-lengths.

[1] *Ibid.*, pp. 65–66.

[2] *Astrophysical Journal*, **32**, 217, 1910.

It appears that the wave-lengths for the two lines λ 6297 and λ 6322 agree closely with those given by Kayser and come into almost exact agreement when the differences in the standards are taken into account, while for the three remaining lines the differences from Kayser's values are far outside the limits of error. It was at first exceedingly puzzling that lines in such close proximity to each other and to the standards, as are these five lines, should give values differing so widely from Kayser's. We soon convinced ourselves, however, that these were real differences and could not be attributed to errors of measurement. In seeking for an explanation, we compared our results with the behavior of the lines under pressure as found by Gale and Adams.[1] From their results we give in the sixth column of Table I the group to which the individual lines belong according to their classification, and in the seventh column the displacements to the red under a pressure of 8 atmospheres above normal. In the case of lines that could not be measured on these plates we give the results from inspection. It is in general easy to determine the group or the type of displacement by inspection, even when no measurements are possible. The line at λ 6302 shows on their plates a tremendous displacement to the red, similar to λ 6301, but too diffuse for measurement. It is at once apparent from inspection of the table that our

TABLE I

International Standards	Kayser's Adjusted	Mt. Wilson	Kayser	Kayser—Mt. Wilson	Group	Pressure of 8 Atm. above Normal
6265.145	6265.145	....	....	0.000	*b*	0.070 Å.
....	....	6297.802	6297.804	+0.002	*b*	0.068
....	....	6301.519	6301.528	+0.009	*d*	0.25
....	....	6302.511	6302.522	+0.011	*d*	Similar to λ 6301 but unmeasurable
6318.028	6318.031	....	....	+0.003	*b*	0.080
....	....	6322.697	6322.698	+0.001	*b*	Group *b* by inspection
6335.341	6335.339	....	....	−0.002	*b*	0.074
....	....	6336.843	6336.850	+0.007	*d*	0.26
6393.612	6393.612	....	....	0.000	*b*	0.072

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 58; *Astrophysical Journal*, **35**, 18, 1912.

results are related to theirs, and that the lines showing such tremendous displacements to the red under pressure on the laboratory plates are the lines showing a lessened wave-length on our plates. These lines belong to group *d* of their class 5, of which they say:[1]

> Almost all of the lines belonging to it occur in the yellow and red portions of the spectrum, and all show enormous displacements. The widening of these lines and their lack of symmetry are so great, however, that many of them are practically incapable of measurement, and for the others the degree of accuracy is extremely low. The measures when made are upon the maximum, which is always upon the violet side of the center of the line.

The first thought was that in the case of unsymmetrical lines the two types of gratings might conceivably give the lines a different appearance. The plane grating having no astigmatism reproduces the exact form of the lines, while the great astigmatism of the concave grating tends to obliterate the differences between the middle and the extremities of the lines, giving them a more uniform appearance throughout their length. This difference in the behavior of the two types of gratings, if effective, would tend, however, in the case of the plane grating to give a longer wave-length for lines so unsymmetrical on the red side, while our measurements gave shorter wave-lengths for these lines. It then occurred to us that the differences were of the order that the differences in atmospheric pressure between the Pasadena laboratory and the observatory on Mount Wilson would produce. The elevation of Mount Wilson is 5886 feet (1794 m), the mean barometric height being 25.4 inches (62.2 cm). The elevation of the Pasadena laboratory is about 800 feet (244 m), so that the difference of altitude corresponds to a change of approximately one-fifth of an atmosphere. Under this decrease of pressure the lines under consideration would undergo an absolute displacement of 0.006 Ångström to the violet, on the basis of the measurements of Gale and Adams. Considering the difficulty of the measurement of these plates, it seemed probable that the cause of the discrepancies would be found in the extreme sensitiveness of these lines to changes of pressure. As to the appearance of these lines under a pressure of 8 atmospheres above normal, Gale and Adams say:[1]

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 58; *Astrophysica Journal*, **35**, 15, 1912.

> Group *d* is made up of a very few lines in the violet, a fair-sized group in the greenish-yellow, and a small number in the red, all of which show immense displacements. The lines are bright and widened enormously to the red, the wings extending sometimes from 5 to 10 Ångström units. The precision of measurement upon these lines necessarily is very low, in some cases the determination amounting to little more than an estimate of the maximum within the broad band.

The preliminary work seemed to promise interesting and important results, and it was then decided to pursue the investigation further. No one questions the adaptability of the plane grating to differential measurements, but in the plan here proposed the absolute wave-lengths were to be determined both on Mount Wilson and in the Pasadena laboratory. In this way the pressure-shifts would be determined by the differences, while for lines belonging to the same groups as the standards two independent determinations of wave-lengths would be obtained.

APPARATUS

The following investigations were made upon two series of plates:

1. A series taken on Mount Wilson with the 30-foot (9 m) Littrow spectrograph used in connection with the 60-foot tower telescope, in which a plane grating by Michelson was used. This grating has an available ruled surface of 2.25 inches (57.1 mm) × 4.88 inches (124 mm) and gives excellent definition for both bright and dark lines.

2. A series of plates made for us by Mr. Babcock with the 30-foot spectrograph of the Pasadena laboratory, in which another Michelson grating was used.

Thus the two series were made separately by two observers with two different instruments. In general the second order of the spectrum was employed, with a scale of approximately 1 mm =0.88 Ångström, but for the detailed investigation of particular regions the third order was employed in which the scale of the plates is approximately 1 mm = 0.56 Ångström. The second order was used for the purpose of having a large number of standards upon each plate, and in order that the scale might be comparable with that used by Professor Kayser in obtaining his list of standards of the third order, since at first it was thought that the accuracy obtainable by means of the plane grating might be shown by a comparison of our results with those already published by Professor Kayser. Later it developed that a more convincing test of their precision could be made by a comparison of our results for Pasadena and the summit of Mount Wilson.

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[1] *Op. cit.*, pp. 31–32.

The arc used in both series is of the type suggested by Pfund,[1] in which a bead of iron oxide rests in a small cup-shaped bowl of the lower positive electrode consisting of an iron rod. The upper electrode is also of iron and carries a brass bushing to prevent overheating of the electrode. The arc was fed with a current of about 6 amperes from a 110-volt direct-current circuit. This type of arc proves to be very satisfactory in the steadiness of its burning, even for periods of an hour.

METHOD OF REDUCTION

The objection raised by the users of the concave grating to the employment of the plane grating for interpolating between standards is, of course, that the scale of the spectrum produced by the plane grating varies continuously along the plate. In practice the tilt of the photographic plate in the spectrograph of the Littrow type is such that it is tangent to the focal curve of the lens, and with an achromatic lens of 30 feet focus, plates 17 inches (43 cm) long may be made so nearly coincident with the curve for their whole length that the definition of the lines is excellent over the full extent of the plate. The scale is then so nearly a linear function of the wave-length that for runs of 50 to 60 Ångströms it is practically linear within the limits of measurement. In every case the scale of the plate at any point is given by the ordinates of a smooth curve whose abscissae are the wave-lengths of the spectral region covered by the plate. There can be no irregularities in the course of such a curve, as at each point it is a function of the corresponding point of the smooth color-curve of the lens employed, and of the angular distance from the middle of the plate. It is the practically linear character of the curve representing the scale of the plate that makes it possible to use the plane grating for interpolating between standards, and the inherent smoothness of the curve that makes it feasible to test the consistency of a series consisting of several standards. In the reduction of our plates the curve giving the scale of an individual plate was found by obtaining the factor (interval in Ångströms between two successive standards divided by the measured interval between the standards) for each two successive standards of the second order. These factors were carried to five significant figures, and plotted as ordinates with the mean wave-lengths of the corresponding intervals as abscissae. A smooth curve was drawn through the points, or sometimes straight lines were drawn from point to point, both methods yielding the same final results. Such curves are shown in Plate XVI, and will be discussed later in this paper.

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[1] *Astrophysical Journal*, **27**, 296, 1908.

In interpolating to obtain the wave-lengths of intermediate lines, only lines were considered which were situated between two standards on the plate under reduction; that is, lines near the ends of the plates and beyond the last standards at either end were not measured. To obtain such lines a series of overlapping plates was used. In calculating the wave-length of any line it was referred to the nearest standard of lesser and also to the nearest standard of greater wave-length. The reduction factors were read from the curve at the points whose abscissae were the means of the wave-lengths of the required line and the standards of lesser and greater wave-length, the approximate wave-length of the line required being known or previously obtained. It will be seen that the course of the curve at the points at which the factors are taken is influenced not alone by the ordinate of the curve fixed by the two standards directly involved, but by the standards on either side of those to which the required line is immediately referred. Hence, the wave-length of the intermediate line is based upon at least four standards and the agreement between the results of the forward and back interpolations furnishes a basis for judging of the consistency of the standards involved, and the method binds the determination of the wave-length of the intermediate line to the four standards.

The measurement of the plates was done mainly upon a Toepfer comparator with a screw 300 mm long, and upon a smaller Toepfer comparator with a screw 150 mm long. Some plates, however, were measured upon Gaertner comparators with screws 80 mm long. In all cases the periodic errors were known to be negligible, and the errors of run were carefully investigated and the corrections applied to the measurements. The plates were measured red to right and red to left. At least four settings were made on each line in the two positions, bringing the cross-wire to the center of the line alternately from the right and left. In many instances, particularly in the case of the standards and some lines difficult to measure, the number of settings was doubled and sometimes tripled. Single and double cross-wires were employed, their use depending upon the intensity of the plates. In obtaining the dispersion-curve from the standards, it would be desirable to measure over the whole length of a plate without changing its position on the comparator. This we were not able to do even with the largest comparator, which required one break in the series. The conditions are less favorable as the range of the screws becomes shorter, and there is a great loss of time, as well as greater liability to error, in measuring overlapping sections of the plate in order to piece the sections together. In the latter case special care is needed in lining up the spectra and the screw. The error introduced by lack of parallelism between the spectra and the screw is not so serious in interpolating between two standards as in obtaining the distances between successive standards upon which the course of the dispersion-curve of the plate depends. A comparator is now under construction in the observatory instrument shop especially adapted to work of this kind, with which a plate 50 cm long can be measured without changing its adjustment. With this instrument it will be possible to obtain standards upon plates taken with higher dispersion, and accordingly to reach a higher degree of accuracy in obtaining a dispersion-curve for testing the consistency of a series of standards.

THE TESTING OF THE INTERNATIONAL STANDARDS

REGION λ 5975–λ 6494

For this region international standards of the second order are available which belong to a single group when classified according to pressure-shift, and over the narrow region under investigation have the same pressure-shift per atmosphere. They have, therefore, the same relative wave-lengths under wide variations of pressure, and hence are suitable for comparing the wave-lengths of other lines measured both in Pasadena and on Mount Wilson. For convenience of reference these standards are assembled in Table II together with the data from Gale and Adams as to pressure-shift, Kayser's adjusted values, and their deviations from the international standards.

TABLE II

STANDARDS OF THE SECOND ORDER

International Standards	Group	Δ at 8 Atm.	Kayser's Adjusted	I.−K.
(5975.354)	*b*	0.054	5975.354	0.000
6027.059	*b*	0.062	6027.062	−0.003
6065.492	*b*	0.077	6065.489	+0.003
6137.701	*b*	0.078	6137.703	−0.002
6191.568	*b*	0.086	6191.568	0.000
6230.734	*b*	0.070	6230.734	0.000
6265.145	*b*	0.070	6265.145	0.000
6318.028	*b*	0.080	6318.031	−0.003
6335.341	*b*	0.074	6335.339	+0.002
6393.612	*b*	0.072	6393.612	0.000
6430.859	*b*	0.068	6430.848	+0.011
6494.993	*b*	0.065	6494.994	−0.001
Mean....................		0.071		
Mean shift per atmosphere		0.009		

The line at λ 5975 is not a standard of the second order, but a standard was needed near this wave-length, as it was desirable to include the two lines at λ 6003 and λ 6008 in the investigation. It was known from an inspection of the plates of Gale and Adams that these lines were enormously widened and displaced to the red, under a pressure of 9 atmospheres, and, in fact, Mr. Adams made a tentative measurement of the displacements of these two lines on one plate but did not consider the results of sufficient accuracy to be included in their published list. They are given in our Table VI. The region is poor in lines and λ 5975 is not of good quality. It is, however, the only line available, and it belongs to the same group as the international standards, and therefore retains its relative wave-length at observing-stations at different elevations, an essential property of standards, as will appear in the course of this investigation. The wave-length given by Kayser for this line was adopted provisionally.

The inherent smoothness of the dispersion-curve for a plate makes it possible to test the consistency of a series of standards with a degree of accuracy which depends upon the length of the intervals between the standards and the precision of the measurements of the distances between the standards on the plate. This is of such great importance in the examination of standards that we give in Table III the complete data for such a curve extending over a range of about 300 Ångströms (between λ 6191 and λ 6494).

TABLE III

International Standards	Intervals	Distances	Factors	Mean λ	Kayser's Adjusted Values	Factors
6191.568					6191.568	
	39.166	45.7586 mm	0.85593	6211.151		0.85593
6230.734					6230.734	
	34.411	40.2802	0.85429	6247.940		0.85429
6265.145					6265.145	
	52.883	62.0582	0.85215	6291.586		0.85220
6318.028					6318.031	
	17.313	20.3567	0.85048	6326.684		0.85024
6335.341					6335.339	
	58.271	68.6640	0.84864	6364.476		0.84867
6393.612					6393.612	
	37.247	44.0138	0.84626	6412.236		0.84601
6430.859					6430.848	
	64.134	76.0395	0.84343	6462.926		0.84359
6494.993					6494.994	

The measurements were made on spectra of the second order taken on plates 43 cm long, inclined to the axis of the spectrograph to bring the plate tangent to the focal curve of the spectrographic lens of 30 feet (9 m) focus. In the sixth column are given the adjusted values according to Kayser, and in the seventh column the corresponding factors. Our curves were plotted with the reduction factors as ordinates on such a scale that 1/16 of an inch

(1.6 mm) represented one unit in the fourth place, and in interpolating we read the factor from the curve to the fifth significant figure. The wave-lengths were plotted as abscissae on such a scale that one of the above divisions represented one Ångström. The original curves from which Plate XVI was reduced were prepared in our draughting-room by Mr. Nichols; the data for the curves were given to him and he was requested to locate the points with great precision. Curve *a*, shown on this plate, corresponds to the data in the fourth and fifth columns of the table. A smooth curve was drawn, and, as is seen, the points fall upon the curve in a most satisfactory way. These data are the means of fourteen measurements and are practically free from accidental errors. Each measurement has given a similar curve but not quite so smooth as the composite curve. Upon the same plate are plotted the points given by using Kayser's adjusted values for the standards. The first three standards agree so that points 1 and 2 coincide. Point 3 is very slightly above, point 4 very much below, point 5 above, point 6 below, and point 7 above the smooth curve. That is, the points determined from Kayser's adjusted values fall in such a way that a smooth curve cannot be drawn upon which the points all lie. A glance at the curve shows at once how consistent with each other are the international standards, and how irregular are the adjusted values. The precision of the method is quite remarkable; a change of 0.002 Ångström in an interval distinctly displaces the corresponding point. The first interval changed by Kayser is the third—52.883 Ångströms—and though this long interval is lengthened only by 0.003 Ångström the ordinate of the point is increased five units in the fifth place. The fourth interval —17.313 Ångströms—is decreased by 0.005 Ångström which displaces the point downward twenty-four units in the fifth place. The fifth point is raised by increasing the interval from 58.271 to 58.273 Ångströms. The sixth point is an important one as it involves a line for which Kayser's adjusted value differs much from the international standard. In reference to this he says:[1]

> This [his] method of measurement has also yielded values for the standards themselves, which I regard as somewhat more accurate than the secondary

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[1] *Astrophysical Journal*, **32**, 217, 1910.

international standards, inasmuch as they are adjusted. They are in general in good accord and only in a few cases is the difference large, in the case of λ 6430 reaching the amount of 0.012 Ångström. It remains to be investigated whether my value is more accurate than the other.

Referring to the curve, it will be seen that point 6 involving this line is greatly displaced; in fact, the point is lowered by 25 units in the fifth place; and point 7, also involving this line, is raised 16 units in the fifth place. It will be noticed that if the wrong value is assigned to one wave-length of a series, the points in which this wave-length are involved are displaced one up and one down so that in such a case the value at fault can easily be ascertained. Judged by the results of this examination of these eight lines, the values for the international standards form a consistent series, no one of which probably contains an error exceeding 0.001 Ångström. The line λ 6430 is an excellent line for measurement, hard and sharp on all of our plates. The values by the three independent observers employing the interference method agree well, viz.:

Fabry-Buisson	Eversheim	Pfund
6430.859	6430.862	6430.855

It is difficult to understand how all of these measurements could be sufficiently in error for the wave-length to be such as Kayser gives it, namely 6430.848, a value not included within the range of the other three. It would tend to destroy faith in the precision of the interference method if such errors were found in the case of lines so excellent for measurement as λ 6430. The method which we illustrate of testing the adjustment of standards is capable of detecting an error of 0.002 Ångström in the case of standards 50 Ångströms apart, and depends only upon the accuracy of the measurements of their distances apart on the photographic plate, values which can be determined to a very high degree of precision. It is essential that a sufficient number of standards be found upon one plate, and with high dispersion this condition requires a plate of great length. These conditions will be well fulfilled by the new 75-foot spectrograph on Mount Wilson, in which a plate 40 inches (100 cm) long can be used. A series of overlapping plates is necessary in order that the lines under investigation may not be too near the end of the series under consideration. The curve *b* on Plate XVI is drawn from data similar to that given in Table III, and is based on 28 measurements of plates covering the region λ 5975–λ 6265, thus overlapping the first region so that points 5 and 6 of this curve are points 1 and 2 on curve *a*. The international and Kayser's adjusted values are:

International..	(5975.354)	6027.059	6065.492	6137.701	6191.568	6230.734	6265.145
Kayser.......	.354	.062	.489	.703	.568	.734	.145
Int.—Kayser..	.000	−.003	+.003	−.002	.000	.000	.000

As in the other region, the points determined from the international values fall on the curve in a very satisfactory way, while the four points involving the three adjusted values fall alternately above and below. The line λ 5975, as before mentioned, is not an international standard, but the value assigned to it by Kayser appears to fit into the series of international standards. It belongs to the same group when classified according to pressure-shift. It is, however, a line difficult to measure with accuracy and hence not suitable for a standard of the second order. Judged by this curve the relative wave-lengths of the international standards λ 6027–λ 6137 are free from errors as great as 0.001 Ångström.

REGION λ 5371–λ 5658

This region is considered by itself because of two difficulties that arise. The first is due to the fact that the international standards involved belong to two groups when classified according to pressure-shift, and that in these groups the relative wave-lengths change a measurable amount with a decrease in pressure of one-fifth of an atmosphere, the change between Pasadena and the observatory on Mount Wilson. The second difficulty is that some adjustments are indicated in the international standards. The standards and related data are given in Table IV.

The first section of the table contains lines of group *a* (Gale and Adams), the flame lines, for which the displacements at 8 atmospheres were very accurately determined by them. The lines in the second section of the table were provisionally classified by them in group *d*, the lines showing great widening and displacement to the red under pressure. The precision of measurement of the displacements of these lines at 8 atmospheres is low, as they have said. The relative change in wave-length between the two sections of the table is 0.003 Ångström for a pressure-change of one-fifth of an atmosphere. After our previous experience in the red region we expected to detect this change in wave-length upon the plates taken upon Mount Wilson. It ought to manifest itself by the point determined by λ 5506 and λ 5569, the terminal and initial lines of the two sets of standards, being slightly displaced upward on the dispersion-curve. We show the results in curve *c* in Plate XVI. The data for the curve are the means of 20 measurements and should be practically free from accidental errors. The mean of the two standards λ 5497 and λ 5506 was used in plotting the curve in order to weight the intervals between standards more equally. In the case of an interval so short as that between these two lines, an error of a few ten-thousandths of an Ångström in their wave-length, or a few ten-thousandths of a millimeter in the measured distance between the lines, displaces the point very markedly.

TABLE IV

STANDARDS OF THE SECOND ORDER

International Standards	Group	Δ at 8 Atmospheres	Kayser	I.−K.
5371.495	*a*	0.029	5371.490	+0.005
5405.780	*a*	0.027	5405.778	+0.002
5434.527	*a*	0.027	5434.527	0.000
5455.614	*a*	0.029	5455.616	−0.002
5497.522	*a*	0.030	5497.521	+0.001
5506.784	*a*	0.031	5506.783	+0.001
Mean Δ		0.029		
Mean Δ per atmosphere		0.0036		
5569.633	sub *d*	0.14	5569.630	+0.003
5586.772	sub *d*	0.12	5586.774	−0.002
5615.661	sub *d*	0.13	5615.667	−0.006
5658.836	sub *d*	0.15	5658.846	−0.010
Mean Δ		0.14		
Mean Δ per atmosphere		0.017		

Point 5 is the one determined from λ 5502, which is the mean of λ 5497 and λ 5506, and λ 5569. It falls, however, very near the curve, while point 6 is distinctly above the curve. This was somewhat surprising, and at first a little disconcerting. The points 2 and 3 are plainly displaced, indicating a small error in the wave-length of λ 5434, the only line concerned with both points. Later when the plates taken in the laboratory in Pasadena were reduced and the dispersion-curves for this region were plotted it at once became evident where the difficulty lay. Curve *f*, Plate XVI, is based upon 20 measurements made on plates taken in Pasadena. Points 2 and 3 are displaced as on the curve for the Mount Wilson plates, confirming the indication of a probable error in λ 5434. It also shows displacements of points 5 and 6 from the mean curve, thus indicating an error in λ 5569. The wave-lengths of the lines λ 5434 and λ 5569, in terms of the other standards, can be obtained by interpolation from these curves. The wave-lengths so determined differ by 0.002 and 0.001 Ångström respectively from the international means for these lines. The second, third, and fourth columns of Table V are adjusted to these values.

TABLE V

PROPOSED ADJUSTMENTS

INTERNATIONAL STANDARDS	PASADENA	MOUNT WILSON	
		A	B
5371.495	5371.495	5371.495	5371.495
5405.780	5405.780	5405.780	5405.780
5434.527	$5434.52\underline{9}$	$5434.52\underline{9}$	$5434.52\underline{9}$
5455.614	5455.614	5455.614	5455.614
5497.522	5497.522	5497.522	5497.522
5506.784	5506.784	5506.784	5506.784
5569.633	$5569.63\underline{4}$	$5569.63\underline{1}$	$5569.63\underline{4}$
5586.772	5586.772	$5586.7\underline{69}$	5586.772
5615.661	5615.661	$5615.6\underline{58}$	5615.661
5658.836	5658.836	$5658.83\underline{3}$	5658.836

Curves are given on Plate XVI corresponding to the four columns of Table V. Those based upon the first column are the curves *c* and *f*, showing the relative wave-lengths of the unadjusted standards for Mount Wilson and Pasadena, respectively. Curve *g* is based upon the adjusted wave-lengths given in the second column as determined from the measurement of the standards on the Pasadena plates. It now has a smooth run and so also has curve *d*, which corresponds to the third column in which the suggested changes have been made on λ 5434 and λ 5569. The wave-lengths of the second group of standards have been corrected for their displacement of 0.003 Ångström, on account of the decreased atmospheric pressure on the mountain, relative to the flame lines of the first section of the table. This change having been allowed for, they ought to form a consistent series; as is seen, the points determined from the mountain measurements now fall upon the curve. Then curve *e* was drawn, using the wave-lengths in the fourth column, in which the suggested changes in the Pasadena values have been made so that they form a consistent series, but no consideration is taken of the relative change in wave-length of the two groups of standards under the pressure-change of one-fifth of an atmosphere that occurs in passing from the altitude of Pasadena to the observatory on Mount Wilson. With these adjustments in the low-altitude values, points 2 and 3 fall on the curve, and point 5, depending upon the terminal and initial lines of the two groups of standards, is displaced slightly upward. It was expected that this would be the case when the mountain plates for this region were first reduced and the point was found to fall on the curve. It appears from the observational data here given that the international values for the wave-lengths of λ 5434 and λ 5569 are slightly in error, and that under the decreased pressure on Mount Wilson the wave-length of λ 5569 was shortened so that its actual wave-length differed only by 0.002 Ångström from that given in the table of the international standards. At the altitude of Mount Wilson it formed a part of a practically consistent series with the flame lines, and therefore no great irregularity was shown in the curve at the point where the two groups joined. The uncertainty regarding point 5 in the first reduction of the mountain plates, using the international values, was caused by the long interval—63 Ångströms—between the terminal and initial lines of the two groups of standards, by the partial compensation by the displacement due to decrease of pressure, and especially by the relatively large displacement of point 6 in the same direction due to the small error in λ 5569 effective over the short interval—17 Ångströms—between it and λ 5586. The manner in which these results confirm one another, however, furnishes strong grounds for believing that they correspond to the facts of the case, and illustrates the precision of the method. The corrections suggested are within the range covered by the international determinations of the individual standards, as the comparison shows.

Fabry and Buisson	Eversheim	Pfund	Suggested	Kayser
5434.530	.524	.528	.529	.527
5569.632	.636	.631	.634	.630

Of the ten standards in this region Kayser suggests adjustments in nine. In case successive lines are given algebraically equal increments, the interval is not changed, but the intervals preceding and following such a series of adjustments are altered and the positions of the corresponding points of the dispersion-curve therefore displaced. The points for the dispersion-curve calculated from Kayser's adjusted wave-lengths in the fourth column of Table IV are shown on curve *h*, Plate XVI. The smooth curve is the same as *g*. Point 2 falls upon the curve. The standards inclosing this point differ by equal increments from those upon which curve *g* is based, so that the interval remains unaltered; the preceding and following points, however, are displaced; 1 and 3 by 8 and 18 units respectively in the fifth place; 4 and 5 in the opposite direction by 5 units in the fifth place. Especially to be considered are points 6, 7, and 8, as these depend upon wave-lengths for which Kayser's suggested adjustments are −0.003, +0.002, +0.006, and +0.010 Ångström. The interval to which point 6, greatly displaced, corresponds is a short one—17 Ångströms—so that decreasing one standard by 0.003 Ångström and increasing the other by 0.002 Ångström produced a change in the factor of 32 units in the fifth place. The position of point 8 depends upon the relative wave-lengths of λ 5615 and λ 5658. Professor Kayser suggests an increase of 0.006 Ångström for the first and an increase of 0.010

Ångström for the last. The point is thereby raised by 9 units in the fifth place, but if the value for λ 5615 had not been increased, point 8 would have been raised 13 units more; that the suggested changes in the preceding wave-lengths were not justified is shown by the positions of points 6 and 7. The evidence, therefore, from this part of the curve is opposed to these changes in the international standards. The adjustments suggested by Professor Kayser indicated that large and systematic errors were involved in the determinations of the international standards by the interference method, as the suggested wave-lengths for these lines are not embraced within the values found by the three independent observers.

Fabry and Buisson	Eversheim	Pfund	Kayser
5615.658	.662	.663	.667
5658.835	.838	.835	.846

From the evidence furnished by the dispersion-curves it appears that none of the international standards in the region λ 5371–λ 5658 is affected with a relative error as great as 0.002 Ångström except λ 5434, and that for other lines the error probably does not amount to 0.001 Ångström except for λ 5569. If any change in the wave-length of λ 5658 is indicated by the dispersion-curve, it is a small decrease rather than a large increase; the only point, however, involving this line is the terminal one, and owing to its position the amount of the error, in case there is a small one, cannot be determined accurately; yet the evidence seems decisive against the large positive correction suggested by Professor Kayser.

The displacements of a few units in the fifth place of the factors are well within the limits of error that occur in reading the factors from the curves. We have usually checked each other when taking the factors from the curves in the interpolations for the standards of the third order, and we rarely differ by 2 units in the fifth place. The scale is greatly reduced in the reproduction shown on Plate XVI, but the larger displacements are easily seen. With the dispersion of the plates taken in the second order an error of 0.002 Ångström in the wave-length of the standard, when referred to the neighboring standards at a distance of 50 Ångströms, would displace the points involving the line in error by 3 units in the fifth place, alternately up and down, and by proportionately greater amounts in the case of more closely spaced standards. The delicacy of the method appeared in adjusting the corrections to λ 5434 and λ 5569. These were found to be slightly in excess of 0.002 and 0.001 Ångström respectively; in using the values 0.003 and 0.002 Ångström it was seen that the lines were overcorrected, while in the case of the values suggested they are slightly undercorrected.

In obtaining the international standards of the second order, it was hoped that the standards would be accurate to 0.001 Ångström in the visible spectrum, and it appears from our examination of the region λ 5371–λ 6494 that practically this hope has been realized, as we have not found errors to exceed that limit except in the case of one line. With secondary standards whose wave-lengths are known to such exactness it will be easily possible to reach a like precision for good lines in the case of the tertiary standards.

WAVE-LENGTH DETERMINATION

REGION λ 5371–λ 6494

In arranging the results of our measurements we found that the lines showing displacements to the red under pressure fall into the groups proposed by Gale and Adams in an important paper on the spectra of iron and titanium under pressure.[1]

Group a.—This involves the well-known flame lines,[2] i.e., the lines relatively strengthened in low-temperature sources, such as the flame of the arc, the low-current arc, and the electric furnace.[3] The lines of this group in the yellow-green show small but definite pressure displacements, the mean being 0.0036 Ångström per atmosphere in the arc.[4]

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[1] *Contributions from Mount Wilson Solar Observatory*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

[2] De Watteville, *Philosophical Transactions*, A **204**, 139, 1904.

[3] Hale, Adams, and Gale, *Contributions from the Mount Wilson Solar Observatory*, No. 11; *Astrophysical Journal*, **24**, 185, 1906; Adams, *Contributions from the Mount Wilson Solar Observatory*, No. 40; *Astrophysical Journal*, **30**, 86, 1909; King, *Contributions from the Mount Wilson Solar Observatory*, No. 53; *Astrophysical Journal*, **34**, 37, 1911; King, *Contributions from the Mount Wilson Solar Observatory*, No. 60; *Astrophysical Journal*, **35**, 183, 1912.

[4] Gale and Adams, *op. cit.*

Group b.—To this group many lines belong; in fact all lines of moderate displacement under pressure are assigned to it for the present. These are bright and symmetrically widened under pressure, and show a mean pressure displacement of 0.009 Ångström per atmosphere for the lines in the region λ 5975–λ 6678 according to Gale and Adams.

Group c.—Group *c* has no representatives in this region.

Group d.—This contains lines showing immense displacements to the red under pressure. The lines are bright and greatly widened to the red under pressure. We have been led to divide group *d*, calling the separate portion sub-group *d*. The lines are similar in behavior under pressure, but show much smaller displacements.

Group e.—To the groups suggested by Gale and Adams we have added a group consisting of lines that remain bright and are greatly displaced to the violet and unsymmetrically widened to the violet under pressure.

DISCUSSION

LINES GREATLY DISPLACED TO THE RED

In Table VI the Pasadena and Mount Wilson values for the wave-lengths are given in the second and third columns respectively. The sixth column contains the differences Pasadena minus Mountain; the ninth and tenth columns show the differences Kayser minus Pasadena or minus mean, and Rowland minus Pasadena or minus mean. In the last column are given the displacements for 8 atmospheres according to Gale and Adams, in the case of lines for which they have given the data. For the other lines we give the results from inspection of their plates. When the lines are so diffuse under pressure that no measurements of value can be made we have said "unmeasurable," though the displacement of the maximum is easy to see. In some cases it has not been possible to fix the type by inspection, but the differences Pasadena−Mount Wilson, and Rowland−Pasadena have shown the group to which the line belongs.

The mean difference, Pasadena−Mount Wilson, for the lines of group *d* in the yellow-green is 0.0075 Ångström. This corresponds to a change in pressure of one-fifth of an atmosphere, or a displacement per atmosphere of 0.0375 Ångström relative to the standards, on the assumption that the differences, Pasadena—Mount Wilson, are attributable entirely to pressure displacement. The standards are displaced to the red 0.0036 Ångström per atmosphere. The absolute displacement is therefore 0.041 Ångström per atmosphere, an amount in excess of the values found by Gale and Adams for these lines, but they say their measurements were little more in some cases than "an estimate of the maximum within the broad band." The mean difference, Pasadena—Mount Wilson, for the lines of group *d* in the red is 0.0095 Ångström; this becomes 0.048 Ångström per atmosphere relative to the standards of group *b*, which show displacements to the red of 0.009 Ångström per atmosphere. The absolute displacement to the red is then 0.057 Ångström per atmosphere, an amount again in excess of the value found by Gale and Adams. On the whole, however, the degree of agreement is surprising rather than otherwise. Assuming that the displacement varies as the cube of the wave-length, the relation found by Gale and Adams for the lines of iron belonging to a common group, the agreement between the observed and calculated values for group *d*, yellow-green, based upon the value 0.057 Ångström for group *d*, red, is within the limits of error, viz., group *d* (yellow-green), observed 0.041 Ångström, calculated 0.038 Ångström. Neither the small pressure-changes of about one-fifth of an atmosphere taken advantage of in this investigation, nor the high pressures used by Gale and Adams are well adapted to the study of lines of this type, and it is purposed to examine *in vacuo* and under normal pressure the behavior of an extended list of lines belonging to groups *d* and *e*.

Sub-Group d.—The mean displacement per atmosphere for the lines of this group, found by Gale and Adams, is 0.019 Ångström to the red. Our results are in complete agreement with this, as we found that the intervals between the international standards of this group and the standards of group *a*, the flame lines, remained constant when the relative displacements for a decrease of pressure of one-fifth of an atmosphere were taken into account. As a basis, displacements of 0.0036 Ångström per atmosphere for the flame-line standards and of 0.019 Ångström per atmosphere for

TABLE VI

LINES GREATLY DISPLACED AND UNSYMMETRICALLY WIDENED UNDER PRESSURE

Not Recommended for Standards

GROUP	INTERNATIONAL WAVE-LENGTHS		MEAN DEVIATION		P.−MT.	WIDTHS IN ÅNGSTRÖMS		KAYSER−PASADENA	ROWLAND−PASADENA	UNDER 9 ATMOSPHERES
	Pasadena	Mount Wilson	P.	Mt.		Pasadena	Mt.			
Iron *d*, green	5393.188(20)	.182(21)	5	4	+0.006	0.100	0.105	−0.002	0.187	Δ=0.14 Å
	5476.587(33)	.578(10)	4	3	+0.009	0.108	0.113	−0.006	0.191	Δ=0.11
					+0.0075	0.104	0.109		0.189	
								K.−Mean	R.−Mean	
Iron sub *d*	5569.634(s)							−0.004	0.214	Δ=0.14 Å
	5572.859(9)	.858(10)	4	3	+0.001	0.120	0.128	−0.001	0.216	Δ=0.14
	5576.109(17)	.107(15)	6	5	+0.002	0.086	0.090	−0.006	0.212	Δ=0.16
	5586.772(s)							+0.002	0.219	Δ=0.12
	5602.958(5)	.964(11)	4	4	−0.006	0.100	0.100	+0.001	0.225	Δ=0.15
	5615.661(s)							+0.006	0.216	Δ=0.13
	5624.559(19)	.560(12)	3	2	−0.001	0.125	0.126	+0.003	0.210	Δ=0.16
	5638.275(11)	.280(4)	4	3	−0.005	0.078	0.108	+0.012	0.211	Δ=0.15
	5658.836(s)							+0.010	0.216	Δ=0.15
					−0.002	0.102	0.110		0.215	
								K.−P.	R.−P.	
Iron *d*, red	5976.816(14)	.804(19)	5	4	+0.012	0.093	0.105	−0.016	0.191	Diffuse. Max. to red. Unmeas.
	5983.712(18)	.705(28)	6	2	+0.007	0.119	0.135	−0.003	0.196	5984 displ. to v. overlaps
	6003.051(11)	.038(26)	6	6	+0.013	0.121	0.125	−0.022	0.188	Δ=0.38 Å
	6008.595(11)	.581(25)	6	7	+0.014	0.124	0.125	−0.015	0.190	Δ=0.40
	6147.844(6)	.836(8)	4	3	+0.008	0.064	0.102	0.000	0.196	Indeterm. Normal arc weak
	6151.636(4)	.628(4)	4	4	+0.008	0.097	0.107	−0.003	0.198	Indeterm. Normal arc weak

Iron *d*, red —*Cont'd*	6180.225(7)	.216(10)	5	6	+0.009	0.084	0.120	+0.005	0.195	Indeterm. Normal arc weak
	6232.669(11)	.662(24)	4	3	+0.007	0.089	0.101	0.000	0.187	Diffuse. Max. to red. Unmeas.
	6246.350(12)	.337(36)	4	4	+0.013	0.123	0.135	−0.005	0.185	Δ=0.28 Å
	6301.531(16)	.518(18)	4	4	+0.013	0.093	0.109	−0.003	0.187	Δ=0.25
	6302.520(11)	.511(17)	4	3	+0.009	0.083	0.084	+0.002	0.189	Diffuse. Max. to red. Unmeas.
	6336.851(16)	.843(17)	4	3	+0.008	0.084	0.098	−0.001	0.197	Δ=0.26 Å
	6400.026(6)	.020(14)	4	2	+0.006	0.123	0.137	+0.010	0.191	Δ=0.24
	6408.044(13)	.038(8)	3	3	+0.006	0.072	0.096	+0.001	0.189	Diffuse. Max. to red. Unmeas.
	6411.678(16)	.668(14)	3	3	+0.010	0.108	0.137	−0.005	0.187	Δ=0.23 Å
					+0.0095	0.098	0.114	+0.018 −0.073	0.191	
Mn	6013.528(20)	.516(5)	4	4	+0.012	0.108	0.109	−0.012	0.187	Diffuse. Max. to red. Unmeas.
	6016.668(17)	.663(13)	6	8	+0.005	0.118	0.123	−0.002	0.193	Diffuse. Max. to red. Unmeas.
	6021.830(13)	.824(9)	5	3	+0.006	0.133	0.137	−0.009	0.186	Diffuse. Max. to red. Unmeas.
					+0.008	0.120	0.123	−0.023	0.189	
Iron *e*	5383.353(7)	.371(8)	9	4	−0.018	0.141	0.147	+0.007	0.225	Diffuse. Max. to v. Unmeas.
	5410.890(13)	.911(8)	6	2	−0.021	0.096	0.108	+0.012	0.234	Diffuse. Max. to v. Unmeas.
	5415.175(10)	.195(13)	6	3	−0.020	0.118	0.122	+0.009	0.241	Diffuse. Max. to v. Unmeas.
	5424.038(11)	.060(12)	6	5	−0.022	0.136	0.138	+0.012	0.252	Diffuse. Max. to v. Unmeas.
	5543.173(7)	.185(5)	6	4	−0.012	0.096	0.106	+0.011	0.241	Indeterm.
	5554.872(14)	.887(3)	6	3	−0.015	0.090	0.109	+0.006	0.250	Diffuse. Max. to v. Unmeas.

TABLE VI—*Continued*

GROUP	INTERNATIONAL WAVE-LENGTHS		MEAN DEVIATION		P.—MT.	WIDTHS IN ÅNGSTRÖMS		KAYSER—PASADENA	ROWLAND—PASADENA	UNDER 9 ATMOSPHERES
	Pasadena	Mount Wilson	P.	Mt.		Pasadena	Mt.			
Iron *e* —*Cont'd*	5565.688(17)	.702(4)	7	4	−0.014	0.111	0.112	−0.003	0.243	5563 displ. to red overlaps
	5598.279(10)	.303(4)	8	1	−0.024	0.105	0.125	+0.013	0.245	No material
	5984.796(15)	.807(26)	5	7	−0.011	0.124	0.139	−0.001	0.244	5983 displ. to red overlaps
	5987.050(17)	.058(28)	3	4	−0.008	0.120	0.135	−0.005	0.240	Diffuse. Max. to v. Unmeas.
	6007.961(9)	.969(17)	5	5	−0.008	0.125	0.150	−0.008	0.225	Indeterm. Normal arc weak.
	6024.051(16)	.059(29)	5	4	−0.008	0.188	0.199	−0.004	0.230	Diffuse. Max. to v. Unmeas.
	6042.083(11)	.093(20)	6	4	−0.010	0.088	0.109	+0.009	0.232	Diffuse. Max. to v. Unmeas.
	6055.983(11)	.995(22)	6	6	−0.012	0.107	0.133	+0.009	0.244	Diffuse. Max. to v. Unmeas.
	6078.470(14)	.482(21)	8	5	−0.012	0.135	0.136	+0.006	0.240	Diffuse. Max. to v. Unmeas.
					−0.014	0.119	0.131	+0.094 −0.021	0.239	

the lines of sub-group *d* were employed. In other words, when the international standards of those two groups formed a consistent system in Pasadena they remained consistent on Mount Wilson when the displacements of the lines of sub-group *d* relative to the lines of group *a* were allowed for, but otherwise not. That the lines of sub-group *d* do not belong to group *d* is again clearly evidenced from the values of the differences, Rowland—Pasadena, of which more will be said later.

Sub-group *d*, as far as now known, consists of 9 lines in the yellow-green, 4 of which are among the international standards of the second order. The other 5 were measured on the Pasadena and Mount Wilson plates with a mean difference between the two stations of 0.002 Ångström. If the lines belong to the same group as the standards used, in this case those of sub-group *d*, the two measurements should agree. Considering the extremely poor quality of the standards and of the measured lines, the agreement may be regarded as satisfactory, their displacements under pressure agreeing within the limits of error with the displacements of the standards, a result already found by Gale and Adams.

In dealing with standards of this quality, the question of their availability for such an exacting purpose at once arises. These lines are greatly displaced and unsymmetrically widened under pressure. If it were a case of displacement only, the lines still remaining symmetrical, adjustments could be made for such changes of pressure as occur between sea-level and the mountain observatories, and the lines would still be usable for standards; but they are in practice usually unsymmetrical, the amount of dissymmetry depending upon the pressure and the quantity of vapor in the source, and, in general, two observers will not agree upon individual lines. This has been the case with the authors of this paper, but the means derived from the measures made upon a large number of lines show a good degree of agreement. To be of service in a series of standards in which errors are expected not to exceed 0.002 Ångström, the quality of a line should be such that a reasonable number of measurements will give that degree of precision. We show in Table IX the results of our individual measures of the distances in millimeters between the lines on 10 exposures

TABLE VII

LINES MODERATELY DISPLACED AND SYMMETRICALLY WIDENED UNDER PRESSURE

Recommended for Standards

GROUP	INTERNATIONAL WAVE-LENGTHS		MEAN DEVIATION		P.−MT.	MEAN	KAYSER−MEAN	ROWLAND−MEAN	UNDER PRESSURE OF 9 ATM.
	Pasadena	Mount Wilson	P.	Mt.					
a......	5371.495(s)	....	..	..	....	....	−0.005	complex	Δ=0.029 Å
a......	5405.780(s)	....	..	..	....	....	−0.002	0.209	Δ=0.027
a......	5429.702(13)	.702(20)	1	2	0.000	5429.702	−0.001	0.209	Δ=0.029
a......	5434.529(s)	....	..	..	....	....	−0.002	0.211	Δ=0.027
a......	5446.919(33)	.920(20)	3	3	−0.001	5446.919	−0.001	0.211	Δ=0.031
a......	5455.614(s)	....	..	..	....	....	+0.002	0.220	Δ=0.029
a......	5497.522(s)	....	..	..	....	....	−0.001	0.213	Δ=0.030
a......	5501.469(33)	.471(15)	2	2	−0.002	5501.470	−0.001	0.213	Δ=0.030
a......	5506.784(s)	....	..	..	....	....	−0.001	0.216	Δ=0.031
a......	5535.419(12)	.419(12)	3	4	0.000	5535.419	+0.001	0.225	Δ=0.034
?......	5543.944(1)	.944(12)	..	..	0.000	5543.944	0.000	0.213	
?......	5563.613(15)	.612(5)	4	4	+0.001	5563.613	−0.005	0.211	
							+0.003 −0.019	0.214	
b......	5975.354	....	..	..	....	....	0.000	0.221	Δ=0.054 Å
b......	6027.059(s)	....	..	..	....	....	+0.003	0.215	Δ=0.062
b......	6065.492(s)	....	..	..	....	....	−0.003	0.217	Δ=0.077
?......	6127.913(15)	.912(16)	5	3	+0.001	6127.912	+0.015	0.212	....
b......	6136.626(22)	.624(21)	1	2	+0.002	6136.625	+0.003	0.204	Δ=0.082
?......	6136.998(14)	7.000(12)	5	3	−0.002	6136.999	+0.013	0.211	....
b......	6137.701(s)	....	..	..	....	....	+0.002	0.214	Δ=0.078
b......	6157.731(18)	.731(13)	5	2	0.000	6157.731	+0.009	0.214	Δ=0.041
?......	6165.367(18)	.366(18)	5	3	+0.001	6165.366	+0.021	0.211	....
b......	6173.341(21)	.343(17)	7	2	−0.002	6173.342	+0.008	0.211	Δ=0.067
b......	6191.568(s)	....	..	..	....	....	0.000	0.211	Δ=0.086

b......	6200.322(9)	.322(21)	3	3	0.000	6200.322	+0.008	0.205	Δ=0.079 Å
b......	6213.437(12)	.439(31)	4	2	−0.002	6213.438	0.000	0.206	Δ=0.072
?......	6215.150(9)	.152(19)	5	4	−0.002	6215.151	+0.002	0.209	....
b......	6219.287(17)	.290(34)	5	2	−0.003	6219.289	0.000	0.205	Δ=0.073
b......	6230.734(s)	....	..	..	....	....	0.000	0.209	Δ=0.070
b......	6252.569(17)	.567(37)	3	2	+0.002	6252.568	−0.001	0.205	Δ=0.077
b......	6254.267(17)	.268(37)	2	2	−0.001	6254.268	+0.001	complex	Δ=0.064
b......	6265.145(s)	....	..	..	....	....	0.000	0.203	Δ=0.070
b......	6297.800(24)	.802(40)	2	2	−0.002	6297.801	+0.003	0.206	Δ=0.068
?......	6315.310(14)	.313(22)	3	3	−0.003	6315.312	+0.011	0.205	....
b......	6318.028(s)	....	..	..	....	....	+0.003	0.211	Δ=0.080
?......	6322.693(21)	.695(34)	2	2	−0.002	6322.694	+0.004	0.213	....
b......	6335.341(s)	....	..	..	....	....	−0.002	0.213	Δ=0.074
?......	6344.159(2)	.159(6)	0	4	0.000	6344.159	+0.005	0.212	....
?......	6355.040(7)	.039(9)	2	2	+0.001	6355.039	+0.006	0.207	....
b......	6393.612(s)	....	..	..	....	....	0.000	0.208	Δ=0.072
b......	6421.363(16)	.362(14)	2	2	+0.001	6421.363	−0.009	0.207	Δ=0.068
b......	6430.859(s)	....	..	..	....	....	−0.011	0.207	Δ=0.068
b......	6494.993(s)	....	..	..	....	....	+0.001	0.220	Δ=0.065
							+0.118 −0.026	0.210	

TABLE VIII

LINES OF QUESTIONABLE UTILITY AS STANDARDS

GROUP	INTERNATIONAL WAVE-LENGTHS		MEAN DEVIATION		P.—MT.	MEAN	K.—MEAN	REMARKS
	Pasadena	Mount Wilson	P.	Mt.				
	5379.588(4)	.587(3)	1	2	+0.001	5379.588	−0.005	Material insuff. Quality poor
	5400.507(6)	.504(4)	3	4	+0.003	5400.506	+0.004	Material insuff. Quality poor
	5445.039(8)	.037(12)	5	6	+0.002	5445.038	−0.001	From best plates. Very faint
?.....	5462.958(4)	.956(5)	3	2	+0.002	5462.957	+0.007	From plates showing best separation. Lines diffuse. Merged under pressure.
?.....	5463.268(9)	.268(4)	2	2	0.000	5463.268	+0.004	Like λ 6102–6103
	5473.917(28)	.916(6)	3	5	+0.001	5473.917	−0.007	Measures difficult and uncertain
a.....	5476.295(33)	.298(3)	3	4	−0.003	5476.296	−0.002	Near diffuse line λ 5476.587. Sep. difficult
b?....	6020.178(5)	.176(21)	7	2	+0.002	6020.177	−0.010	*Fe* line distant 0.169 Å
	6089.571(14)	.568(11)	5	3	+0.003	6089.570	+0.011	Too faint on our plates for good measures
?.....	6102.179(13)	.181(21)	3	3	−0.002	6102.180	+0.002	Diffuse. Merges with 6103 under pressure. Like λ 5462–5463
?.....	6103.183(2)	.181(2)	8	2	+0.002	6103.182	+0.010	*Fe* line distant 0.114 Å
b.....	6256.	.375(35)	..	2	....	6256.375	+0.002	Blend with nickel on valley plates
	6280.623(3)	.628(28)	4	4	−0.005	6280.626	+0.005	Insuff. valley material. Very faint
	6462.740(8)	.737(10)	8	2	+0.003	6462.738	−0.004	Insuff. material for difficult line

upon a plate in the third order, covering this region, with a scale 1 mm = 0.58 Ångström. We include two lines of group *a* for a comparison between the measures upon good and poor lines. The mean deviations are given in the last line. The abbreviations S. and W. refer to St. John and Ware.

TABLE IX

QUALITY OF SECONDARY STANDARDS λ 5569–λ 5658

GROUP *a*		SUB-GROUP *d*							
5497–5506		5506–5569		5569–5586		5586–5615		5615–5658	
S.	W.	S.	W.	S.	W.	S.	W.	S.	W.
15.918	.920	108.428	.427	29.715	.710	50.175	.174	75.283	.277
.917	.918	.430	.430	.696	.698	.178	.181	.287	.286
.916	.920	.419	.421	.708	.708	.177	.176	.281	.286
.918	.923	.432	.431	.692	.698	.173	.176	.289	.284
.921	.917	.423	.425	.692	.695	.178	.180	.302	.301
.920	.918	.431	.432	.699	.690	.180	.186	.286	.287
.917	.917	.431	.428	.682	.675	.188	.184	.294	.298
.920	.916	.424	.420	.700	.706	.178	.177	.286	.290
.920	.917	.439	.430	.688	.703	.175	.178	.288	.286
.919	.920	.440	.424	.694	.697	.175	.177	.299	.295
15.9186	.9186	108.430	.427	29.697	.698	50.178	.179	75.289	.289
0.0014	.0017	.0049	.0034	.0072	.0070	.0027	.0031	.0051	.0056

The agreement between our measures for the group *a* interval is complete; and if we had been obliged to rely upon one or two exposures, the divergence from the general mean would not have made a serious error. In the case of intervals involving the lines of sub-group *d*, however, our measures for the same exposures vary greatly and capriciously, but the general means are in fair agreement. It is evident that very divergent results would be obtained by using single exposures, and even a fair degree of accuracy can be had only by the use of an inconveniently large number of plates, a sufficient quantity of which in many cases would not be available.

Lines of the character of sub-group *d* will present different appearances upon spectra taken with concave and plane gratings. The astigmatism of the concave grating greatly lengthens the lines and tends to obscure the dissymmetry by distributing it along the length of the line. This would be a source of error, particularly if the ends of the lines were cut off as in the case of a close-lying comparison spectrum. When the image of the middle of the arc is held stationary upon the slit of a plane-grating spectrograph, the dissymmetry of such a line becomes apparent; but when the image plays over the slit as in the case of an unsteady arc, the same line upon the spectrum plate may be long and apparently symmetrical. Since the inherent difficulties of the measurement of such lines are great, and the sources of error so many and insidious, we have not included these lines among those which we recommend for standards. The rejection of these lines from the series of standards would enlarge the region near λ 5800 for which the Committee has recommended that barium lines be used. In a still higher degree, the same reasoning holds in the case of the lines of group *d* and the still greater difficulties of measurement render them in our judgment unsuitable for standards of the third order.

LINES GREATLY DISPLACED TO THE VIOLET UNDER PRESSURE

Group e.—When the data from the Mount Wilson and Pasadena plates were finally assembled, some lines were noticed for which the mountain plates gave larger values than the valley plates. The quality of these lines is poor, and it was at first thought that the errors of measurement were proving greater than was expected; but it soon appeared probable that the differences between the mountain and the valley wave-lengths were real, and that the lines constitute a group the members of which are widened and greatly displaced to the violet under pressure, and therefore to the red under the lessened pressure at the elevation of Mount Wilson. In continuation of the grouping scheme of Gale and Adams, we have formed the group *e*, whose definition has already been given. On inspection of the plates of Gale and Adams taken under a pressure of 9 atmospheres with a comparison spectrum at atmospheric pressure, which they kindly placed at our disposal, these lines are seen to be enormously widened with the maximum displaced to the violet. They appear as though blown to the violet under this pressure without a maximum sufficiently pronounced for measurement, but the direction and character of the displacement can be determined with certainty by inspection.

These lines occur in the yellow-green and the red. The mean of the differences, Pasadena—Mount Wilson, is −0.014 Ångström. On the assumption that the lessened wave-length in Pasadena is due to the difference in atmospheric pressure, the displacement relative to the standards is −0.070 Ångström per atmosphere. The mean displacement of the standards per atmosphere is +0.006 Ångström; hence the absolute displacement is −0.070 Ångström +0.006 Ångström = −0.064 Ångström. This would mean an enormous displacement for these lines, and there has been as much hesitancy in accepting displacements to the violet under pressure even to a small amount, as there has been in accepting displacements to the red of the order of those which the measurements given in this paper appear to show.

Since the lines showing these great displacements are unsymmetrically widened under pressure, in the case of group *d* to the red and of group *e* to the violet, it has been thought by others, notably Fabry and Buisson,[1] that such displacements were only apparent and arose from the difficulties inherent in the comparative measurement of such lines. Widening and displacement under pressure are intimately connected, and it is exceedingly difficult to determine whether there is actual displacement of a line, when the widths of the line are different under the two conditions of pressure. To render our data so far as possible free from such errors, and to guard against their entering into the differences, Pasadena—Mount Wilson, in such a way as to produce or increase these differences we measured the widths of the lines and based the comparison only upon plates for which the widths of the lines on the mountain plates equaled or slightly exceeded the widths of the corresponding lines on the Pasadena plates. The measurements of the widths are given in the seventh and eighth columns of Table VI.

As to the lines showing the enormous displacements to the red, the results of this paper are in accord with the measurements of Gale and Adams, and no doubt of their reality could remain in the mind of anyone who has had opportunity to examine the Gale and Adams plates, even if careful measurements had not been made. The mean width on the mountain plates of the lines showing displacement to the violet under pressure is 0.131 Ångström and on the Pasadena plates, 0.119 Ångström. The increase of width in the case of such lines is unsymmetrical, whether the increase is due to increased pressure or to greater density of the radiating vapor, and is largely on the violet side of the line. The mean width of the lines of this group on the mountain plates exceeds the mean width on the Pasadena plates by 0.012 Ångström, so that in the absence of pressure-shift, the wave-lengths should have been less on the mountain than in the valley by approximately 0.006 Ångström. As a matter of fact we found them longer by 0.014 Ångström. On the assumption of no pressure displacement to the violet this would imply an average error of 0.020 Ångström in the measurement of lines whose mean width is 0.120 Ångström. The mean deviations averaged 0.006 Ångström for the Pasadena plates and 0.004 Ångström for the mountain plates, with mean probable errors of 0.0017 Ångström and 0.0011 Ångström respectively. The mountain and valley plates were measured by the same observers, reduced by the same methods, the lines referred to the same standards, and the plates intermingled in the course of the measurement, so that the effects due to systematic error and personal equations were eliminated as completely as possible. In view of the above considerations, and the degree of precision obtained in the case of normal lines, there seems sufficient ground for adopting the direct interpretation of the data, viz., that the lines of groups *d* and *e* are greatly displaced as well as unsymmetrically widened by pressure, and to the red and violet respectively.

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[1] *Comptes Rendus*, **148**, 688, 1240, 1909.

RELATION BETWEEN WAVE-LENGTHS IN ARC AND IN ROWLAND'S TABLE

Reference has been made at various times in this paper to the differences, Rowland—Pasadena. The subject deserves a somewhat fuller discussion. The relation has been of service in the present investigation in classifying the lines into groups which agree with those formed upon the basis of pressure-shift. In the comparison we have used the wave-lengths in Pasadena in the case of the lines in groups *d*, *e*, and *Mn*; for the lines of groups *a*, *b*, and sub *d*, we have used the means of the mountain and valley plates. The differences, Rowland—Kayser, show the same classification, as appears from a consideration of Table X.

That there is a physical basis for the classification cannot be doubted. This is particularly evident in the case of groups *d*, *e*, and *Mn*. It is not so evident from the table in the case of groups *a*, *b*, and sub *d*, but it becomes evident when their respective pressure-shifts 0.0036 Ångström, 0.009 Ångström, 0.019 Ångström, are taken into account. It would be interesting to discuss these results somewhat fully from the point of view of some solar problems, but such a discussion would lead far afield, and investigations now in progress are furnishing so much additional material bearing upon the subject that any discussion now would be premature.

TABLE X

ROWLAND DIFFERENCES

	a	*b*	*d*	Sub *d*	*e*	*Mn*
S. and W.	0.214	0.210	0.191	0.215	0.239	0.189
Kayser.	0.215	0.207	0.195	0.213	0.233	0.196

Much has been said about the irregular and apparently capricious differences that are obtained in comparing the wave-lengths of Rowland's table with wave-lengths in the arc, and efforts have been made to determine some factor or operator by which the Rowland wave-lengths can be converted into international units. It is clear from Table X that the apparently large irregularities in the Rowland differences are not inaccuracies, but represent real differences. This is clearer still when one considers that the lines in groups *d*, *e*, and *Mn* are nearly all sharp lines in the solar spectrum, and hence the accidental errors in Rowland's table in the case of these lines are a minimum. It is equally clear that no one factor can be found by which the wave-lengths can be converted from one system into the other with satisfactory accuracy, even for a limited region of the spectrum. This late justification of Rowland's values for individual lines has of course no bearing upon the systematic errors pointed out by Fabry and Perot.[1] In fact the curve plotted from the data in Table VII shows the same course as theirs. The method proposed by them for passing from one system to the other is alone capable of yielding satisfactory results.

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[1] *Astrophysical Journal*, **15**, 272, 1902.

LINES RECOMMENDED FOR STANDARDS

The criterion applied in selecting the lines suitable for use as standards of the third order has been the close agreement of the wave-lengths as determined from the mountain and from the Pasadena plates. The lines yielding the same values from the two series of plates either belong to the same group as the standards, or undergo practically the same displacement for small changes in pressure. The lines examined are separated into three sections, namely: λ 5371–λ 5563 referred to the flame-line standards, λ 5569–λ 5658 referred to the standards of sub-group *d*, and λ 5975–λ 6494 referred to standards belonging to group *b*. The second section has already been considered and for the reasons given omitted from the list of recommended lines. Two groups of lines, *d* and *e*, occurring in the first and third sections, have also been dropped from the list of available lines because of their extreme sensitiveness to changes in the pressure and density of the emitting vapor, manifesting itself in displacement and great dissymmetry. There remain only 25 lines which we are able to recommend as tertiary standards. The distribution of these lines in reference to the 17 international standards of the second order may be seen in Table VII. The results of our examination of 100 lines are as follows:

Recommended	Standards of the second order	17
	Standards of the third order	25
Rejected	Lines of group *d*	17
	Lines of sub-group *d*	9
	Lines of group *e*	15
	Lines of manganese	3
Questionable		14
		100

We have not been able to measure the many lines of intensity 2 of Kayser's list, as they either did not appear on our plates, or were too faint for the purpose of measurement. Of the 14 lines in the questionable list, a large proportion will probably prove available and be extremely useful as faint-line standards when their wave-lengths are definitively determined; but our material was so insufficient and the quality of the lines so poor that we do not include them in the list of recommended standards on the basis of our measurements even though the precision is apparently high (mean p.e. 0.0016 Ångström for the Pasadena plates, p.e. 0.0011 Ångström for the mountain plates). It would appear from the agreement of the mountain and valley measurements that the lines belong to the same groups as the standards to which they were referred, but in four instances this is not the case. The pair of lines λ 5462-5463 was found by Adams[1] to be much stronger in the flame than in the core of the arc, and therefore would appear to belong to the group of flame lines, but under a pressure of 9 atmospheres their appearance differs widely from the appearance of the flame lines proper. They seem related to the pair λ 6102–6103. In the normal arc they are all hazy, and under a pressure of 9 atmospheres they appear enormously diffused with no indication of displacement.

THE PRECISION OF THE MEASUREMENTS

The precision that may be obtained by the use of a plane grating is best shown by the agreement between the wave-lengths obtained from the two series of plates in the case of lines belonging to the same group as the standards used in their measurement. In Table VII the measurements of such lines are given. The mean of the differences, Pasadena—Mount Wilson, taken without regard to sign, is 0.0010 Ångström. This seems to us a more satisfactory measure of the precision obtained than the mean probable errors of 0.0007 Ångström and 0.0006 Ångström in the case of the valley and mountain plates respectively. As these measurements are absolute and not differential, the precision may be taken as representing the degree of accuracy given by the plane grating in interpolating between the international standards of the second order in the case of lines of good quality. This is the same order of precision obtained by one of us in a previous investigation[2] when the conclusion was drawn that with homogeneous standards an accuracy of 0.001 Ångström could be obtained in the case of the best lines.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 40; *Astrophysical Journal*, **30**, 126, 1909.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 44; *Astrophysical Journal*, **31**, 143, 1910.

SOME RELATED CONSIDERATIONS

In comparing our results with those published by Kayser, systematic differences appear, for some of which we can find no explanation. In the case of the lines of groups *b*, sub *d*, and the three lines of manganese, our values from the Pasadena plates are larger than his in the mean by 0.0037 Ångström; in the case of the lines of group *e*, our values from the Pasadena plates are smaller in the mean by 0.0056 Ångström. As these lines show more or less dissymmetry, the first group widening more on the red edge, the latter on the violet edge when the pressure or density of the emitting vapor is increased, such systematic differences may represent the personal equations of the observers in setting upon lines of this character, or may depend upon the different appearances that the two types of gratings would give to such lines.

There appear systematic differences between our results and those of Kayser in the case of lines belonging to groups *a* and *b*, for which our two series of plates show a high degree of agreement. These differences persist after allowance has been made for the different values of the secondary standards to which the tertiaries are referred in the two instances. For the lines referred to the flame-line standards of group *a*, λ 5371–λ 5463, Kayser−S. and W.=+0.0003 Ångström; for the lines of group *b*, λ 5975–λ 6355, Kayser−S. and W.=+0.005 Ångström; for the two lines, λ 6421 and λ 6462, the differences are accounted for by the large difference in the wave-length of the standard λ 6430. Thus at the beginning and end of the list the values agree, but in the intermediate region the difference is larger than it seems possible to assign to accidental errors. In a paper published during the preparation of this article for the press, Goos[1] reports similar systematic differences between his values and those of Kayser for the blue-green region which he has investigated by means of a plane grating, and thinks that these deviations are to be explained by the fact that Kayser used a simple linear interpolation between each two of the secondary standards and then averaged the results.

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[1] *Astrophysical Journal*, **35**, 229–230, 1912.

The result of his previous investigation of the conditions which influence the dispersion in the case of the concave grating, and which should be taken into account is stated as follows:

> Es ist bedenklich, bei Konkavgitterspektrogrammen, selbst innerhalb enger Intervalle, linear ohne Anbringung von Korrektionen zu interpolieren, da man nicht im voraus weiss, in welchem Bereich der Platte die Konstanz des Maasstabes ausreichend ist.[1]

In practice the interpolations in the case of the concave grating appear fully as troublesome as in the case of the plane grating, when a high degree of precision is required. With the plane-grating spectrograph of long focus, the dispersion is apparently more nearly linear than it is normal with the concave grating, and between linear and normal dispersion there is not much to choose on the ground of convenience in interpolation. There seems to be no good reason for assuming a priori that the precision is in one case higher or lower than in the other. It appears that in either case the dispersion for each plate must be considered by itself, and its departure from the normal or linear character must be determined in order to fix the interval through which the dispersion is normal or linear to the required degree.

The idea that changes in atmospheric pressure, such as occur in passing from sea-level to the altitudes of modern observatories, may alter the relative wave-lengths of spectrum lines by measurable amounts introduces a new point of view, and suggests other conditions that a series of standards should fulfil when the highest precision is to be obtained. The red region of the spectrum which is especially rich in lines showing great displacements had not been systematically studied before Gale and Adams undertook its examination. In view now of the large amount of observational data accumulated, recognition should be given to the possibility and the probability of introducing errors by neglecting the effects of relative pressure displacement. Even in the case of some standards of the second order the change in relative wave-lengths amounts to 0.003 Ångström on Mount Wilson, and for observatories of greater elevation it may reach 0.005 Ångström. For other iron lines the change is 0.010 Ångström on Mount Wilson, and may reach 0.015 Ångström at the higher stations. There are a number of important observatories at which such changes in wave-length would prove disturbing.

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[1] *Zeitschrift für wissenschaftliche Photographie*, **10**, 206, 1911.

OBSERVATORIES AT HIGH ALTITUDES

Heidelberg, Germany	570 m	Astronomical and Astrophysical Institute. Königstuhl
Berne, Switzerland	573	Observatory of the Cantonal University
Madrid, Spain	655	Astronomical and Meteorological Observatory
San Luis, Argentina	800	Southern Observatory of the Carnegie Institution
Mount Hamilton, California	1283	Lick Observatory
Denver, Colorado	1650	Chamberlin Observatory
Mount Wilson, California	1794	Solar Observatory of the Carnegie Institution
Flagstaff, Arizona	2210	Lowell Observatory
Tacubaya, Mexico	2280	National Observatory of Mexico
Palani Hills, India	2347	Kodaikánal Observatory
Arequipa, Peru	2452	Station of Harvard College Observatory
Bogota, Republic of Colombia	2634	National Observatory of Republic of Colombia
Quito, Ecuador	2908	National Observatory of Ecuador

GENERAL SUMMARY

1. The precision obtainable with the plane-grating spectrograph in determining the absolute wave-lengths of standards of the third order by interpolation between the international standards is 0.001 Ångström in the case of good lines. Two entirely different instruments were used and the mean of the differences between the wave-lengths in the two series is 0.0010 Ångström, a quantity less than the sum of the probable errors. This represents the performance of two similar instruments; whether the actual wave-lengths were determined with this degree of precision or whether there is some obscure systematic error in the methods will appear when more determinations are made by other observers with other instruments.

2. The secondary standards between λ 5371 and λ 6494, except λ 5763, were examined in reference to their relative wave-lengths. The conclusion is that there are no errors in their relative wave-lengths exceeding 0.001 Ångström, except in the case of the line λ 5434, where it reaches 0.002 Ångström.

3. Of the 100 lines studied in the region λ 5371–λ 6494, we find 17 thoroughly suitable for secondary standards, and 25 for tertiary standards; 44 are discarded because of abnormal pressure displacements accompanied with dissymmetry; and 14 are provisionally classified as of questionable utility.

4. In comparing the wave-lengths from the two series of plates, Mount Wilson and Pasadena, it was found that in the case of 20 lines the wave-lengths determined from the valley plates were in the mean 0.009 Ångström longer than the wave-lengths determined from the mountain plates when lines of the same width were compared. All of these lines, that are of sufficient intensity to appear upon the Gale and Adams plates at a pressure of 9 atmospheres, show strongly unsymmetrical widening and large displacements of the maxima to the red. They seem to us inherently unsuitable for standards and therefore have been rejected.

5. It likewise appeared from the comparison of Mount Wilson and Pasadena determinations of wave-lengths that 15 lines gave values on the valley plates shorter than on the mountain plates by 0.014 Ångström, when the comparison was made between lines of equal widths. Upon the plates of Gale and Adams taken at 9 atmospheres, these lines are very unsymmetrically widened and the diffuse maxima displaced to the violet. There seems sufficient reason for considering them a distinct group, the components of which are really displaced to the violet and unsymmetrically widened under pressure. The reasons for rejecting the lines showing great displacement to the red hold in even greater degree for these lines.

6. From the large differences that appear in the amounts by which different lines are displaced under pressure, it would be desirable to know the pressure displacements of all lines that are finally accepted as standards of the second or third order. The secondary standards λ 5569–λ 5658 are a case in point, the differences between the displacements of these lines and the neighboring standards being 0.015 Ångström per atmosphere. The difficulties of exact measurement due to their lack of sharpness and to their dissymmetry are so great that we are forced to omit them from the list of recommended lines. In the selection of barium lines to

supplement the iron lines, a preliminary examination of the barium lines with regard to displacements under pressure is to be recommended; and in extending the series of standards to the red, caution should be especially exercised in the selection of lines, in view of the occurrence in the red of lines showing great pressure displacements and the rapid increase of displacement with wave-length.

Mount Wilson Solar Observatory
May 1912

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OBSERVATIONS OF THE SPECTRUM OF *NOVA GEMINORUM* No. 2

BY WALTER S. ADAMS AND ARNOLD KOHLSCHUTTER

The first observations of the spectrum of *Nova Geminorum* No. 2 were made by us on March 22, nine days after its discovery by Enebo, the delay being due to unfavorable weather and a somewhat late receipt of the announcement of its position. From that time until May 27, observations were continued as the weather and the time at the disposal of the spectrograph permitted.

All of the spectrograms were obtained at the 80-foot focus of the large reflector with the Cassegrain spectrograph. At first a single prism of 63° angle with a camera lens of 102 cm focal length was used, but after April 5 this lens was replaced by one of 46 cm focal length. With the latter lens and suitable tilt of the photographic plate it is possible to obtain good definition throughout the entire spectrum from H_ϵ to H_α with the exception of a limited region near H_β. For purposes of close comparison, however, we have photographed mainly the region between λ 3900 and λ 5000, only two plates having been taken of the less refrangible portion. A list of the photographs follows:

Plate No.	Date	G.M.T.	Camera	Region
γ 1076	1912 March 22	$17^h\ 28^m$	Long	H–λ 5000
1083	23	17 21	Long	H–λ 5000
1087	24	15 36	Long	H–λ 5000
1089	28	16 24	Long	H_β–H_α
1091	30	16 30	Long	H_ϵ–λ 5000
1102	April 3	17 09	Long	H_ϵ–λ 5000
1103	5	17 23	Short	H_ϵ–λ 5000
1104	6	15 51	Short	H_ϵ–λ 5000
1105	6	16 39	Short	H_ϵ–λ 5000
1118	22	16 15	Short	H_ϵ–λ 5000
1149	28	16 21	Short	H_ϵ–λ 5000
1185	May 5	16 08	Short	H_ϵ–λ 5000
1188	10	16 15	Short	H_ϵ–H_α
1201	27	15 50	Short	H_ϵ–λ 5000

In discussing the results obtained from the reduction of these spectra we shall consider the subject under several heads:

1. General characteristics of the spectrum and changes during the observations.
2. Radial velocity.
3. The hydrogen lines.
4. The helium lines.
5. Nebular lines.
6. Probable identifications.

I. GENERAL CHARACTERISTICS OF THE SPECTRUM AND CHANGES DURING THE OBSERVATIONS

The first spectrum of the *Nova*, taken on March 22, showed a strong continuous spectrum with many dark lines, some sharp and narrow and others broad and diffuse. At numerous places faint bright bands are present, in most cases accompanied by strong dark lines, usually double, on the more refrangible side. Apart from hydrogen the more prominent of these bands are due to parhelium. The hydrogen lines are represented by strong bright bands from 20 to 30 Ångströms wide with strong double absorption lines to the violet. Each of the bright hydrogen bands has strong maxima of about equal intensity at the two edges and between the two is a broad faint absorption band at least partially broken up into numerous narrow dark lines. The effect is very similar to that observed by Campbell and Wright in the hydrogen bands of *Nova Persei* and described by them in their well-known memoir.[1]

The most noticeable changes in the spectrum in the days immediately following March 22 were the decrease in intensity of the continuous spectrum, the rapid changes and disappearance of the absorption lines, the very marked alterations in the hydrogen absorption lines, and the rapid changes in the maxima of the bright hydrogen bands. On the photographs of March 23 and 24 the dark hydrogen lines are still strong and double. On March 28, however, they are much weaker and the bright band between them appears like a wing on the bright hydrogen lines. The red line

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[1] *Astrophysical Journal*, **14**, 269, 1901.

H_α shows the effect most strongly. The next spectrogram, obtained on March 30, again shows the strong absorption lines, but each is itself double, thus forming a set of four. On succeeding spectrograms the more refrangible component grows fainter and finally disappears as does the other after persisting somewhat longer.

The two chief maxima of intensity at the edges of the bright hydrogen bands, after remaining approximately equal from March 22 to March 30, show a great change after that time. On March 30 the violet maximum is decidedly broader and somewhat stronger, while on the succeeding spectrogram taken on April 3 the red component is much the more prominent. This continues to hold true to the end of our series of observations on May 27. Within the bands there are numerous changes in the secondary maxima as well.

The main feature of the later photographs of the *Nova* is the gradual change of the spectrum in the direction of the nebular spectrum, which is apparently characteristic of all *Novae*. It is marked chiefly by the following changes:

1. A steady decrease in the intensity of the continuous spectrum.
2. A corresponding increase in the intensity of numerous bright bands in the spectrum, many of which are characteristic of the spectrum of nebulae. The most important of these is the chief nebular line, λ 5007, which is first seen with certainty on April 6. It increases very rapidly after that time and on the last photographs in the latter part of May it is nearly equal to H_β in intensity and one of the strongest features of the spectrum.

The second nebular line, λ 4959, was first seen on a spectrogram of April 22 and from this time until the end of our series of observations it grew rapidly stronger. On April 28 it formed one of a nearly equal pair with the helium line λ 4922 but after that time it was much the stronger of the two.

Other lines which increased greatly in intensity toward the end of the series of observations were the well-known nebular lines λ 4364 and λ 4687. The former is seen as a heavy wing upon the red side of H_γ on photographs taken subsequent to April 22. The line λ 4687 of the principal series of hydrogen was first seen as a faint shading upon the red side of the very bright band λ 4614–λ 4662. It rapidly grew stronger and on the last photograph is a well-marked feature of the spectrum.

The very complex region between λ 4600 and λ 4700 undergoes many changes. On the earliest photographs there is merely a trace of some faint bright bands in this region. Between March 24 and March 30, however, a strong double bright band develops extending from λ 4628 to λ 4670 with the centers of its components at λ 4643 and λ 4662. This band later grows in width and intensity, the width reaching a maximum about April 28 when the entire band extends from λ 4574 to λ 4681. Its intensity is about one-half that of the brightest part of H_β. After this time the band begins to break up into components the brightest of which extends from λ 4622 to λ 4661, its center being at λ 4642. On our last spectrograms this band has an intensity nearly equal to that of H_β. It evidently coincides with the line observed by Campbell in the spectra of nebulae at 464 $\mu\mu$. The changes of intensity during the interval March 22 to May 10 are shown by the curves of Plate XIX.

In giving the results of our measures we shall give the values for four groups of plates. The first consists of the three spectrograms γ 1076, γ 1083, and γ 1087 taken on March 22, 23, and 24. The second group consists of γ 1091–γ 1105, taken between March 30 and April 6. The third group includes γ 1118 and γ 1149, taken April 22 and April 28. The fourth group consists of the photographs taken after May 5.

The less refrangible region from λ 5050 to λ 6600 is considered separately. The wave-lengths given are corrected for radial velocity.

Owing to the very rapid changes in the spectrum there are some cases of apparent contradiction in the results given in a single column; for example, the center of a dark line nearly coincides with the center of a bright band. These are due to changes on the photographs the results of which are grouped, and so are only apparent. It is hardly necessary to say that it is impossible in all cases to distinguish between true absorption lines and dark spaces, as well as between bright bands and portions of the continuous spectrum. Thus complex regions such as λ 4550–λ 4700 may be analyzed in very different ways by different observers.

TABLE I

Portion of Line or Band	Observed Wave-Lengths for Different Plate Groups				Identification
	γ 1076 –γ 1087	γ 1091 –γ 1105	γ 1118 –γ 1149	γ 1185 –γ 1201	
Violet edge bright band.....	......	......	3882.7	3881.5	
Center dark band..........	......	......	3884.7	3885.2	
Center bright band.........	......	......	3891.3	......	H_ζ band λ 3889
Red edge bright band.......	......	......	3899.7	3900.8	
Violet edge bright band.....	3925.0	......	......	......	K band
Narrow dark line..........	3933.9	......	......	......	*Ca* λ 3934
Red edge bright band......	3948.5	......	......	......	
Center dark band or line....	3950.5	3952.0	......	......	
Center faint bright band....	3955.2	3954.4	......	......	
Center dark band or line....	3959.0	3958.0	......	......	
Violet edge bright band.....	3960.9	3962.6	3960.8	3960.7	H_ϵ band λ 3970
Center dark line...........	......	3966.0	......	......	λ 3951–λ 3981
Narrow dark line..........	3968.7	3968.6	3969.2	3967.8	*Ca* λ 3969
Center bright band.........	3970.7	3972.6	3971.2	......	
Center dark line...........	......	3973.4	......	......	
Center bright maximum....	......	3977.6	3977.6	......	
Red edge bright band......	3980.2	3981.9	3982.0	3981.8	
Center dark line...........	3984.1	3983.5	3982.6	......	
Violet edge bright band.....	......	......	3987.1	3986.0	
Center dark band..........	......	4003.6	......	......	
Red edge bright band......	......	4009.0	4006.6	4007.6	
Red edge dark band........	......	4018.2	4018.2	4018.8	
Center faint bright band....	......	4035.0	4034.4	......	
Red edge bright band......	......	......	4052.3	4052.0	
Violet edge bright band.....	......	4062.2	4061.5	4061.8	
Center dark band..........	......	4067.0	......	4066.3	
Center bright band.........	......	4067.9	......	......	Nebular band
Violet edge bright band.....	4069.7	......	......	......	λ 4069
Red edge bright band......	......	4073.6	......	......	
Center dark band..........	4072.9	4075.1	......	4074.0	
Violet edge stronger bright band..................	4077.0.	......	......	......	Probably part of H_δ band
Maximum in dark band....	......	4078.6	......	......	
Violet edge strong dark line..	4080.4	4081.1	......	......	
Center strong dark line.....	4082.5	4083.4	......	4084.0	
Red edge strong dark line...	4085.0	......	......	......	
Center bright band.........	4086.6	4085.2	......	......	
Violet edge dark line.......	4088.9	4087.0	......	......	
Center dark line...........	4090.5	4089.0	......	......	
Violet edge bright band.....	4092.6	4092.8	4089.9	4090.2	H_δ band λ 4102 λ 4081–λ 4113

TABLE I—*Continued*

Portion of Line or Band	Observed Wave-Lengths for Different Plate Groups				Identification
	γ 1076 –γ 1087	γ 1091 –γ 1105	γ 1118 –γ 1149	γ 1185 –γ 1201	
Maximum in bright band	4096.0	......	......	4094.4	
Violet edge dark band	4098.4	......	......	......	
Center dark line	......	......	......	4098.6	
Center bright band	4102.7	4103.7	4100.4	4102.6	
Center dark line	......	4101.8	......	......	
Center dark band	4104.2	4105.4	4105.2	4102.0	
Violet edge bright maximum	......	4105.6	......	......	
Center bright maximum	......	......	4109.4	4108.0	
Red edge dark band	4109.2	......	......	......	
Center dark line	......	4110.0	......	4110.7	
Center bright maximum	4111.1	4110.1	4111.2	......	
Red edge bright band	4113.1	4114.5	4114.6	4115.1	
Center dark line	......	4123.6	......	......	
Center dark line	4133.4	......	......	......	
Violet edge faint bright band	......	......	......	4135.9	
Center dark line	4153.6	4154.3	......	......	*He* band λ 4144
Red edge faint bright band	......	4156.2	......	4157.8	
Center faint dark band	4160.4	4158.2	4160.4	......	
Center dark line	......	......	......	4168.0	
Center faint bright band	4173.1	......	......	......	*He* λ 4169
Violet edge faint bright band	......	4180.9	......	4179.9	
Center bright band	......	4185.1	4182.3	......	
Center dark band	......	4191.6	......	......	
Red edge bright band	4192.7	4190.4	......	......	
Center dark line	4196.7	4197.4	......	......	
Center dark line	......	4200.4	......	4198.8	
Center faint bright band	4200.6	......	......	......	(H′ λ 4201)
Center dark line	......	4206.7	......	......	
Center faint dark line	4210.9	4209.2	......	......	
Violet edge dark band	......	4210.7	......	4212.7	
Center dark band	4213.2	4214.2	4215.6	4213.3	
Center faint bright band	4217.0	......	......	......	
Center dark line	4219.1	4220.2	......	......	
Center strong dark line	4222.5	......	......	4224.6	
Violet edge bright band	4224.0	4223.0	4225.8	......	
Violet edge bright band	......	......	......	4231.0	
Center bright band	4235.2	4236.0	4238.2	......	
Center bright band	......	......	......	4240.6	
Center dark line	......	4234.7	......	......	
Center dark line	4236.0	......	......	......	
Red edge bright band	4246.5	4244.8	......	......	
Center dark line	4248.9	4247.7	4250.0	4248.6	
Red edge bright band	......	4252.8	4252.6	4251.3	
Center dark band	......	4256.3	4255.1	4255.7	

TABLE I—*Continued*

Portion of Line or Band	Observed Wave-Lengths for Different Plate Groups				Identification
	γ 1076 −γ 1087	γ 1091 −γ 1105	γ 1118 −γ 1149	γ 1185 −γ 1201	
Violet edge bright band.....	......	4259.6	4258.4	4259.3	
Center dark line..........	......	......	4263.3	4263.5	
Center faint bright band....	4271.4	4269.7	4269.3	4269.4	Nebular band λ 4265
Violet edge faint bright band	......	4275.6	......	......	
Center dark line...........	4279.5	......	......	......	
Red edge bright band......	......	4280.0	4280.2	4280.0	
Center dark line..........	4283.4	......	4282.8	4281.8	
Center faint bright band....	......	4283.7	......	4285.6	
Center dark line..........	4289.1	......	......	......	
Violet edge bright band.....	4291.4	4292.3	......	......	
Red edge bright band......	......	4292.2	......	......	
Center dark line..........	......	4293.9	......	4294.4	
Center bright band.........	4294.8	......	......	......	
Violet edge bright band.....	......	4297.2	......	......	
Center dark band..........	4302.5	......	4303.4	4304.3	
Center bright band.........	......	4304.8	......	......	
Violet edge bright maximum	4305.5	4306.0	4305.6	......	
Center dark line..........	......	......	......	4306.6	
Center bright maximum....	4310.9	4309.5	......	......	
Center dark line..........	......	4313.0	......	......	(*Ti* λ 4313.0)
Red edge bright band......	......	4313.9	......	......	
Center dark line..........	......	4316.0	4315.6	......	
Red edge bright band......	4317.3	......	......	......	
Center dark line..........	......	4318.0	4317.5	4316.2	
Center strong dark line.....	4320.0	4319.8	......	......	
Violet edge bright band.....	4322.6	4321.9	......	......	
Center bright band.........	4324.5	4323.6	......	......	
Red edge bright band......	4325.9	4325.4	......	......	
Maximum in dark line......	......	4326.2	......	......	
Center dark band..........	4328.4	4327.8	......	......	
Violet edge bright band.....	4330.8	4330.4	4328.6	4329.4	H_γ band λ 4341 λ 4316–λ 4354
Narrow bright maximum ...	4334.2	......	4334.4	4333.8	
Dark line.................	4335.0	4334.2	......	......	
Center bright maximum....	4335.5	4335.6	......	......	
Violet edge dark band......	4336.8	......	......	......	
Narrow dark line..........	4337.4	4337.4	4337.4	4336.9	
Dark line.................	......	4339.8	......	4339.4	
Dark line.................	4342.2	4343.6	......	4343.0	
Center bright band.........	4342.6	4343.7	4341.4	4342.0	
Center broad dark band....	4343.4	4343.3	......	4341.9	
Red edge dark band.........	4349.8	4348.4	......	......	
Dark line.................	4348.7	4350.8	......	......	
Center bright maximum....	4351.1	4350.9	4350.1	4350.5	
Strong narrow maximum....	......	......	......	4351.8	
Red edge maximum........	4353.9	4353.1	......	......	
Red edge bright band......	4353.4	4354.4	4354.4	4353.9	

TABLE I—*Continued*

Portion of Line or Band	Observed Wave-Lengths for Different Plate Groups				Identification
	γ 1076 –γ 1087	γ 1091 –γ 1105	γ 1118 –γ 1149	γ 1185 –γ 1201	
Dark line	4356.3	4355.8	4354.8	4354.6	
Center broad dark band	......	......	......	4361.6	
Center bright wing	4361.4	4359.5	......	......	
Red edge bright wing	4363.3	4365.2	......	......	
Dark line	4364.8	4365.1	......	4364.2	
Center bright band	......	......	......	4364.8	Nebular band λ 4364
Dark line	......	4367.0	......	4368.2	
Violet edge bright band	......	4368.8	......	......	
Dark line	......	4372.6	......	......	
Bright maximum	......	......	......	4373.2	
Violet edge bright band	4376.0	......	......	......	
Red edge bright band	......	......	4379.0	4377.1	
Bright maximum	4379.0	......	......	......	
Center dark band	......	......	4380.0	4380.9	
Bright maximum	......	4382.2	......	......	
Dark line	4384.4	4386.6	......	......	
Center bright band	4386.0	4386.0	......	4388.1	*He* band λ 4388 λ 4376–λ 4397
Dark line	4389.2	......	......	......	
Center faint bright band	4391.3	......	......	......	
Red edge whole bright band	......	......	......	4392.2	
Dark line	4392.6	4392.6	......	......	
Red edge bright band	4395.4	4398.5	......	......	
Dark line	4397.2	......	......	......	
Dark line	4399.4	4399.7	......	4398.9	
Violet edge bright band	4401.2	......	......	......	
Dark line	4402.5	......	......	4403.7	
Violet edge bright band	......	4406.0	4405.8	4406.2	
Dark line	4406.4	......	......	......	
Maximum in bright band	......	4409.4	......	......	
Dark line	4415.7	4416.6	......	4415.9	
Center bright band	4416.5	4418.0	......	4417.8	
Dark line	......	4419.4	4418.2	......	
Dark line	4423.5	4423.0	......	......	
Bright maximum	......	4425.0	4424.7	......	
Red edge bright band	4428.2	......	4429.8	4428.8	
Dark line	4429.0	......	......	4430.0	
Center dark band	4432.3	4431.1	4432.7	4433.2	
Violet edge bright band	4435.4	......	4435.8	4435.8	
Center bright maximum	......	4438.4	......	......	
Center bright band	4442.6	4441.6	4442.1	4443.0	*He* band λ 4438 λ 4436–λ 4450
Violet edge dark band	......	4446.2	4448.1	4447.0	
Strong dark line	......	4446.9	......	......	
Red edge bright band	4450.5	......	......	4449.8	

TABLE I—*Continued*

Portion of Line or Band	Observed Wave-Lengths for Different Plate Groups				Identification
	γ 1076 –γ 1087	γ 1091 –γ 1105	γ 1118 –γ 1149	γ 1185 –γ 1201	
Center dark band	4452.4	4452.2	4452.1	4451.3	
Maximum in dark band	......	......	4455.0	4455.0	
Violet edge bright band	4455.6	4457.9	......	......	
Very strong dark line	4460.8	4460.3	4461.0	......	*He* band λ 4472
Violet edge bright band	4463.0	......	4461.5	4462.5	λ 4452–λ 4485
Bright maximum	......	4465.0	......	4465.0	
Dark line	4467.0	4467.2	......	4467.7	(*Fe* λ 4466.7)
Dark line	......	......	......	4471.2	
Center bright band	......	4473.3	4472.6	4473.8	
Dark line	4477.7	......	......	......	
Center bright maximum	......	4480.6	......	4481.0	(*Mg* λ 4481.4)
Red edge bright band	4486.5	4485.3	4484.6	4484.5	
Dark line	4487.2	......	......	......	
Dark line	4489.3	4488.8	......	4487.8	(*Ti* λ 4488.5)
Center dark band	......	4492.2	4491.0	4490.8	
Dark line	4495.5	4493.8	......	4494.3	(*Fe* λ 4494.7)
Violet edge bright band	4496.3	......	4495.6	......	
Red edge dark band	......	4499.6	......	......	
Dark line	4501.5	......	......	4501.6	(*Ti* λ 4501.4)
Dark line	4505.2	4505.6	......	......	
Dark line	4508.1	4508.0	......	4506.8	(*Fe* λ 4508.5)
Violet edge bright band	......	4508.1	4507.0	4508.1	
Dark line	......	4510.2	......	......	
Dark line	4511.9	4512.9	......	......	
Violet edge stronger bright band	4512.4	4512.1	......	......	
Bright maximum	......	4517.0	......	4516.2	
Dark line	4518.9	4517.8	......	4517.2	
Center whole bright band	......	4520.1	......	4520.5	
Dark line	4522.8	4522.1	......	......	
Center bright band	4522.8	4523.2	......	......	
Dark line	......	4525.5	......	4526.6	(*Fe* λ 4525.3)
Dark line	4529.0	4529.0	......	......	(*Fe* λ 4528.9)
Dark line	......	......	......	4532.0	
Red edge bright band	4533.7	4534.2	......	......	
Dark line	4534.7	......	......	4535.2	
Broad dark line	......	4536.7	......	......	
Dark line	4537.6	4538.3	......	4538.6	
Red edge bright band	......	......	......	4538.4	
Violet edge bright band	4538.7	4539.8	......	......	
Dark line	4543.8	4544.8	......	......	
Red edge bright band	......	......	......	4546.6	
Dark line	4547.0	4547.0	......	......	
Center bright band	4552.4	4551.3	......	......	
Dark line	......	4551.6	......	......	
Dark line	4554.6	4555.0	......	......	
Red edge bright band	......	4562.7	4564.7	......	

TABLE I—*Continued*

PORTION OF LINE OR BAND	OBSERVED WAVE-LENGTHS FOR DIFFERENT PLATE GROUPS				IDENTIFICATION
	γ 1076 –γ 1087	γ 1091 –γ 1105	γ 1118 –γ 1149	γ 1185 –γ 1201	
Narrow dark line	4562.5	......	......	......	
Maximum in dark line	......	4566.2	......	......	
Red edge bright band	4568.6	......	......	4567.0	
Center dark band	4569.1	4569.5	4570.2	4570.5	
Maximum in dark band	4571.9	4570.9	4573.2	4571.4	(*Ti* λ 4572.2)
Violet edge bright band	4573.3	4574.9	4573.7	4575.2	
Dark line	4575.8	4575.6	......	......	
Center bright band	......	4579.4	......	......	
Dark line	4580.9	4580.8	......	4579.9	
Center bright band	4585.7	4586.0	......	......	
Dark line	4586.7	4587.8	......	4585.5	
Center bright maximum	......	4594.8	......	......	
Dark line	......	4596.4	......	......	
Red edge bright band	4598.2	4597.9	......	......	
Dark line	......	4598.9	......	......	
Bright maximum	......	......	......	4600.1	(Nebular 459 μμ)
Dark line	4601.0	4600.6	......	......	
Center bright band	......	4601.0	......	......	
Dark line	4603.3	4603.2	......	......	
Strong dark line	......	4605.1	......	......	
Red edge bright band	4606.3	......	......	......	
Dark line	4608.3	4607.8	......	......	
Center dark band	4610.2	4610.4	......	......	
Center bright band	......	4611.7	......	......	(Nebular λ 4610)
Violet edge bright band	4613.0	4615.5	......	......	
Dark line	......	4617.7	......	4616.4	
Violet edge bright band	......	4621.2	......	4618.4	
Center bright band	......	4622.0	......	......	
Dark line	4623.0	4621.2	......	......	
Violet edge stronger bright band	......	4622.5	4622.4	......	
Dark line	4624.3	4625.7	4626.6	4626.0	
Bright maximum	4627.4	......	......	......	
Center bright band	4631.4	4632.2	......	......	
Center dark band	4632.3	4633.9	......	......	
Center dark line	......	4636.3	......	......	
Bright maximum	4638.4	......	4636.4	......	
Center bright band	......	4640.7	......	4640.8	Nebular 464 μμ
Center dark band	4643.0	......	......	......	
Center bright maximum	......	4643.4	4646.0	......	
Dark line	4646.2	4645.3	......	......	
Red edge bright band	4649.5	......	......	......	
Dark line	......	4651.6	......	4650.7	
Center bright band	......	4654.3	......	......	
Center dark band	4655.9	......	......	4657.0	
Violet edge bright band	4659.2	......	......	......	

TABLE I—*Continued*

Portion of Line or Band	Observed Wave-Lengths for Different Plate Groups				Identification
	γ 1076 –γ 1087	γ 1091 –γ 1105	γ 1118 –γ 1149	γ 1185 –γ 1201	
Center bright maximum	......	4661.9	......	......	(Nebular λ4663)
Red edge bright band	......	4664.0	......	4662.4	
Dark line	......	4667.8	......	4667.0	
Center bright band	4667.4	......	......	......	
Center bright band	4672.8	......	......	......	
Dark line	4674.8	4675.2	......	......	
Violet edge bright band	......	......	......	4674.2	
Red edge bright band	4675.3	4675.0	......	......	
Center bright maximum	......	......	......	4678.4	
Dark line	4678.4	4679.2	......	4679.7	
Center bright maximum	......	4682.3	......	......	Nebular λ 4687
Red edge bright band	4683.4	4682.4	4680.8	......	λ 4674– λ 4700
Dark line maximum	......	4686.1	......	4685.8	
Center bright band	......	......	......	4687.1	
Violet edge bright band	......	4689.0	......	4685.8	
Center bright maximum	......	......	......	4694.8	
Dark line	4694.0	4693.0	4690.7	4692.6	
Bright maximum	......	4696.8	......	.....	
Red edge bright band	......	......	......	4700.3	
Red edge bright band	......	4706.4	4708.6	......	
Center bright maximum	4709.9	4709.1	4707.5	......	
Dark line	......	4720.3	......	......	
Red edge faint bright band	......	4726.6	4725.1	4723.8	
Center faint bright band	4738.5	......	......	......	
Violet edge dark band	......	4744.0	......	......	
Maximum in dark band	4751.6	4752.1	4753.1	4751.6	
Red edge dark band	......	4756.2	......	......	
Dark line	4756.0	4756.2	......	......	
Dark line	4762.0	4762.4	......	......	
Red edge dark band	......	4765.2	......	......	
Violet edge faint bright band	......	......	4772.7	4771.9	
Dark line	4781.4	......	......	4782.2	
Dark line	......	......	......	4789.6	
Center faint bright band	......	4792.6	4793.8	......	
Dark line	......	4794.4	4794.6	......	
Center faint bright band	......	......	......	4804.1	
Violet edge dark band	......	4818.2	4817.6	4816.3	
Dark line	4824.7	4825.3	......	4826.0	
Center dark band	......	4828.9	......	4830.5	
Strong dark line	......	4833.2	......	......	H_β band λ 4862
Violet edge strong dark band	4835.8	......	......	......	λ 4833–λ 4877
Dark line	......	4835.8	......	......	
Center narrow bright band	4837.2	4836.3	......	......	
Center strong dark line	4837.8	4837.9	......	......	
Violet edge bright band	......	4837.8	......	......	

TABLE I—*Continued*

Portion of Line or Band	Observed Wave-Lengths for Different Plate Groups				Identification
	γ 1076 –γ 1087	γ 1091 –γ 1105	γ 1118 –γ 1149	γ 1185 –γ 1201	
Dark line	......	4841.1	......	......	
Center bright band	......	4841.7	......	......	
Red edge dark band	4841.4	4841.5	......	......	
Dark line	......	4842.3	......	4842.8	
Center bright line	4843.6	4842.9	......	......	
Red edge bright band	4845.9	4845.8	......	......	
Center strong dark line	4847.6	4847.6	......	......	
Violet edge bright band	4849.9	4849.8	4847.0	4847.8	
Narrow bright maximum	......	4852.0	......	......	
Bright maximum	4854.1	4854.4	4853.4	4854.0	
Narrow dark line	......	4853.2	......	4852.2	
Bright maximum	......	4855.7	4856.4	......	
Dark line	......	4856.2	......	......	
Violet edge dark band	4856.9	......	......	......	
Center dark line	4858.1	4857.8	4858.5	4859.0	
Center whole bright band	4863.0	4864.0	4862.6	4863.0	
Center dark band	4863.7	4864.5	......	4862.1	
Maximum in dark band	......	4863.9	......	......	
Maximum in dark band	......	4866.6	......	4866.5	
Red edge dark band	4870.7	......	......	......	
Bright maximum	4871.6	4872.3	4870.9	4871.2	
Center strong bright maximum	4872.9	4873.5	......	......	
Red edge bright band	4875.9	4877.6	4877.7	4877.7	
Center bright wing	......	4883.0	......	......	Part of H_β band
Dark line	4885.1	......	......	......	
Red edge bright wing	......	4888.6	......	......	
Dark line	4889.9	4890.1	......	......	
Center strong dark line	......	4896.9	......	4898.2	
Dark line	4900.5	......	......	4901.6	
Center bright band	4905.4	......	......	......	
Center dark band	4909.9	4909.1	4909.0	......	
Maximum in dark band	4911.2	......	......	......	
Violet edge bright band	4912.1	4911.2	......	4911.4	
Violet edge stronger bright band	4913.4	4914.1	4913.7	4912.7	*He* band λ 4922 λ 4901–λ 4938
Dark line	......	4915.7	......	......	
Center bright maximum	......	4917.5	......	......	
Dark line	4920.7	4919.8	4920.3	4921.2	
Center dark band	4925.9	4925.1	......	4923.7	
Center bright band	4925.8	4926.2	4926.2	4924.4	
Center stronger bright band	......	4927.4	......	......	
Red edge bright band	4938.1	4938.0	4938.3	4936.1	
Center strong dark line	......	......	4940.5	4940.7	
Violet edge bright band	......	......	4943.1	4945.8	
Center bright band	......	......	4959.0	4960.1	Nebular λ 4959
Red edge bright band	......	......	4976.3	4973.6	

TABLE I—*Continued*

PORTION OF LINE OR BAND	OBSERVED WAVE-LENGTHS FOR DIFFERENT PLATE GROUPS				IDENTIFICATION
	γ 1076 –γ 1087	γ 1091 –γ 1105	γ 1118 –γ 1149	γ 1185 –γ 1201	
Strong dark line	......	......	......	4978.0	
Violet edge faint bright band	4980.3	......	......	......	
Center faint dark band	......	......	4980.0	4983.3	
Strong dark line	......	......	......	4985.3	
Violet edge bright band	......	4990.8	4991.2	4989.5	
Center bright band	......	4992.8	......	......	
Violet edge stronger bright band	......	4993.5	......	4992.5	
Center strong dark line	4994.7	......	......	......	
Center bright maximum	......	4996.1	......	4997.1	*He* band λ 5016 λ 4995–λ 5032
Red edge bright band	5001.9	5003.7	......	......	
Dark line	5004.5	5003.8	......	5004.0	
Dark line	......	5007.2	......	......	
Violet edge bright band	5006.9	5010.3	......	......	
Center bright band	......	5007.0	5007.8	5007.1	Nebular λ 5007
Center stronger part of bright band	5012.5	5011.9	......	......	
Dark line	5014.3	5015.2	......	5011.7	
Red edge bright band	......	5020.2	5023.6	5022.5	
Center bright band	5019.3	5020.1	......	......	
Dark line	5023.0	5024.2	......	......	
Center bright maximum	......	5027.2	......	......	
Red edge bright band	5032.1	5032.8	......	......	
Violet edge bright band	......	......	......	5040.6	
Center faint bright band	......	......	......	5048.7	*He* band λ 5048 λ 5041–λ 5060
Red edge bright band	......	......	......	5060.1	

PORTION OF LINE OR BAND	OBSERVED WAVE-LENGTHS		IDENTIFICATION
	γ 1089	γ 1188	
Violet edge faint bright band	5160.4	......	
Center bright band	5172.5	5176.7	*Mg b* group
Red edge bright band	5183.5	......	
Center very faint bright band	5239.0	......	
Center faint bright band	5279.0	......	
Violet edge bright band	5308.3	......	
Center bright band	5319.4	......	
Red edge bright band	5332.5	......	
Center faint bright band	5379.1	......	
Violet edge bright band	5566.9	......	
Dark line	5577.2	......	

TABLE I—*Continued*

Portion of Line or Band	Observed Wave-Lengths		Identification
	γ 1089	γ 1188	
Center bright band	5580.4	......	
Red edge bright band	5591.5	......	
Violet edge bright band	5649.2	......	
Violet edge bright band	......	5666.7	
Center bright maximum	......	5676.2	
Center bright band	5680.8	5680.2	
Red edge bright band	......	5693.9	
Red edge bright band	5710.6	......	
Violet edge bright band	5743.1	5742.6	
Center faint dark band	......	5754.5	
Center bright band	5757.3	5755.9	Nebular λ 5752
Bright maximum	......	5765.7	λ 5743–λ 5770
Red edge bright band	5770.0	5770.0	
Violet edge bright band	5847.3	......	
Violet edge bright band	......	5864.7	*He* band λ 5876
Maximum in bright band	5870.1	......	λ 5847–λ 5909
Center bright band	5877.9	5878.1	
Dark line	5880.9	......	
Center stronger part of band	5885.7	......	
Red edge bright band	......	5891.2	
Dark line	5890.3	......	D_2 *Na* λ 5890
Dark line	5896.6	......	D_1 *Na* λ 5896
Red edge bright band	5909.4	......	
Center faint bright band	......	5942.3	
Violet edge faint bright band	5989.0	......	
Center faint bright band	6004.8	......	
Red edge bright band	6017.1	......	
Center faint bright band	6158.8	......	
Center faint bright band	6248.8	......	
Violet edge bright band	6287.7	6289.3	
Center bright band	6302.4	6304.7	Nebular λ 6301
Red edge bright band	6317.8	6320.3	
Violet edge bright band	6352.0	......	
Center bright band	6367.6	6370.0	
Red edge bright band	6382.0	......	
Violet edge bright band	6449.5	......	
Center bright band	6474.1	......	
Center bright maximum	6480.1	......	
Center bright band	......	6486.5	
Dark line	6502.0	......	
Red edge bright band	6509.0	......	
Dark line	6519.6	......	

TABLE I—*Continued*

Portion of Line or Band	Observed Wave-Lengths		Identification
	γ 1089	γ 1188	
Violet edge bright band	6529.7	......	
Center bright band	6536.9	......	Wing on H_α band
Red edge bright band	6543.0	......	
Dark line	6545.1	......	
Violet edge bright band	6548.3	6545.4	
Maximum in bright band	6555.3	......	H_α band λ 6563
Center bright band	6567.0	6569.4	λ 6545–λ 6585
Center dark band	6567.2	......	
Maximum in bright band	6578.6	......	
Red edge bright band	6585.2	......	
Center bright wing	6593.7	......	
Red edge bright band	......	6595.2	
Red edge bright wing	6600.5	......	Part of H_α band
Bright maximum	......	6672	
Center faint bright band	......	6677	*He* λ 6678

2. RADIAL VELOCITY

The principal lines available for the determination of the radial velocity of the *Nova* are the narrow absorption lines H and K of calcium, certain faint lines, for the most part due to iron, which appear on some of the plates, and the narrow lines D_1 and D_2, which are present upon one of the photographs taken in the less refrangible region. Owing to the strong absorption of the glass of the prism employed, the spectrograms are rather weak in the H and K region and the results obtained from these lines are not very accordant. The following is a summary of the values from the various lines:

Plate	Lines	Velocity	Reduction to Sun	Radial Velocity
		km	km	km
γ 1076	H	+40.2	−29.3	+10.9
1083	H, K	+47.0	−29.4	+17.3
1087	H, K	+33.1	−29.3	+ 3.8
1104	H	+35.0	−29.4	+ 5.6
1118	H	+28.5	−27.5	+ 1.0
1089	D_1, D_2	+47.4	−29.5	+17.9
1076	4222, 4528	+47.3	−29.3	+18.0
1083	4222, 4236, 4528	+39.6	−29.4	+10.2
1087	4222, 4250, 4494, 4501, 4528	+35.2	−29.3	+ 5.9

Although the range shown by these observations is rather large, in view of the character of the lines we do not consider any certain variation of velocity as established. The mean of the results as given in the table is

+10 km

and the mean of the final results of the six plates is

+10 km.

Determinations of the radial velocity by other observers are as follows:

Curtiss.........	+ 9 km
Plaskett........	+12 km with a probable variation of 15 km
Küstner........	+ 7.0 km

3. THE HYDROGEN LINES

The bright hydrogen bands are characterized by definite edges upon the red side which can be measured with a very fair degree of accuracy. On the violet side the dark absorption lines upon the earlier photographs form the boundary which seems to persist as the absorption lines grow fainter. These two limits, accordingly, represent the principal part of the emission band, while a broad fainter band extends toward the violet. The strong band is the

CENTERS OF BRIGHT HYDROGEN BANDS

Plate	H_ϵ	H_δ	H_γ	H_β	H_α
γ 1076.......	3971.0	4103.2	4342.4	4863.0	......
1083.......	3970.1	4102.5	4343.3	4862.8	......
1087.......	3970.7	4102.3	4342.2	4862.9	......
1089.......	......	......	......	4862.9	6566.8
1091.......	3972.5	4102.7	4342.2	4863.1	......
1102.......	3972.5	4102.3	4342.8	4863.5	......
1103.......	......	4103.0	4343.1	4863.9	......
1104.......	3972.7	4104.7	4343.1	4867.9	......
1105.......	......	4105.8	4343.9	4864.6	......
1118.......	3972.0	4103.0	4342.2	4862.7	......
1149.......	3970.6	......	4340.9	4862.5	......
1185.......	3971.2	4103.2	4341.3	4862.4	......
1188.......	......	4101.9	4341.9	4863.0	......
1201.......	......	4103.4	4342.4	4863.3	......
Mean.....	3971.5	4103.2	4342.4	4863.3	6566.8
Δ.........	+1.3	+1.3	+1.8	+1.8	+3.8

portion upon which our measures of width and displacement have been made. In the accompanying tables we have collected the results of our measures upon both the dark and the bright hydrogen lines.

An examination of the measures of the bright hydrogen bands shows that as in the case of *Nova Persei* the centers are displaced toward the red. On our photographs we have measured the centers directly, as well as the violet and the red edges of these bands. Accordingly, two independent determinations are available. Collecting all of the results we obtain the table on p. 16.

The displacements from the normal positions of the lines are given opposite Δ in the last row of the table. It is a peculiar fact that these values are better satisfied by a law in which the displacement is directly proportional to the square of the wave-length than they are by one in which it is proportional to the first power such as is found for the dark hydrogen lines and the widths of the bright hydrogen bands. The difference is due almost entirely to H_α for which but one determination is available. A least-squares solution gives the following residuals in the two cases:

	λ	λ^2
H_ϵ	−0.2	0.0
H_δ	−0.2	−0.1
H_γ	+0.2	+0.2
H_β	0.0	−0.1
H_α	+1.3	+0.2

The dark hydrogen lines could be measured satisfactorily upon but a few of the earlier spectrograms. The results follow:

DARK HYDROGEN LINES

Plate	H_ϵ		H_δ		H_γ		H_β		H_α
	I	II	I	II	I	II	I	II	I
γ 1076	......	......	4090.2	4082.2	4328.3	4319.5	4847.6	4837.0	......
1083	3959.0	3950.5	4090.6	4082.4	4328.4	4320.2	4847.5	4837.5	......
1087	3958.9	3950.5	4090.8	4082.8	4328.5	4320.4	4847.7	4839.0	......
1089	......	......	......	......	......	......	4848.0	......	6545.2
Mean	3959.0	3950.5	4090.5	4082.5	4328.4	4320.0	4847.7	4837.8	6545.2
Δ	−11.2	−19.7	−11.4	−19.4	−12.2	−20.6	−13.8	−23.7	−17.8

If we take the values of the displacements of the dark lines, given as Δ in the table, and determine their variation with wave-length we find the relationship obtained by Campbell and Wright for the dark hydrogen lines in *Nova Persei*, and by Plaskett in the case of the present *Nova*—that is, the displacement is directly proportional to the first power of the wave-length. The residuals from a least-squares solution assuming the values of equal weight are as follows:

	Component I O−C	Component II O−C
H_ϵ	+0.2	+0.5
H_δ	0.0	−0.4
H_γ	+0.1	−0.4
H_β	+0.4	+0.3
H_α	−0.4	.....

These residuals are within the limits of error of the measurements.

We have already referred to the fact that on plate γ 1091 taken March 30 each component of the hydrogen lines is itself double, although in the case of H_δ and H_β we have been unable to measure the separate portions of the less refrangible component. The values for this plate are as follows:

	H_δ			H_γ				H_β		
	I	II		I		II		I	II	
		a	*b*	*a*	*b*	*a*	*b*		*a*	*b*
γ 1091....	4088.9	4078.6	4082.2	4326.2	4328.5	4315.9	4319.8	4846.5	4833.2	4837.9
Separation		3.6		2.3		3.9			4.7	

The values of the separation of the two lines forming component II appear to be closely proportional to the wave-length. It is a noteworthy fact that the position of the *b* line of component II in each case occupies the same position as the center of the whole component upon the plates γ 1076–γ 1089. In other words, the doubling of the lines upon γ 1091 is due to a new component formed about 4 Ångströms to the violet of the original lines. The change, accordingly, can hardly be ascribed to anything in the nature of a variation of pressure or to a possible magnetic field, but must rather be due to the action of an additional mass of absorbing gas, and it is probably allied to some of the phenomena of multiple reversal in laboratory spectra.

The widths of the bright hydrogen bands are, of course, influenced by the density of the spectrograms, and similarly the relative widths are affected by the curve of sensitiveness of the photographic plates employed. A comparison of the widths of the lines for the whole series of photographs is of considerable interest, however. In the accompanying table the values are given in Ångström units. Owing to a defect in the photograph at the position of the H_α line on γ 1188, its value is omitted.

WIDTHS OF BRIGHT HYDROGEN BANDS

Plate	H_ϵ	H_δ	H_γ	H_β	H_α
γ 1076.......	18.7	20.8	22.5	26.1	....
1083.......	19.3	20.8	....	26.9	....
1087.......	20.2	19.9	22.4	25.7	....
1089.......	....	....	....	26.3	38.8
1091.......	22.7	23.0	22.0	27.2	....
1102.......	....	24.5	25.6	29.0	....
1103.......	....	24.1	24.0	28.5	....
1104.......	17.4	20.1	23.2	28.5	....
1105.......	....	17.2	22.1	28.2	....
1118.......	20.5	22.0	25.8	29.6	....
1149.......	22.1	27.1	25.7	31.9	....
1185.......	21.0	25.6	25.4	32.1	....
1188.......	....	25.0	24.6	30.1	....
1201.......	....	23.1	22.8	24.8	....
Mean......	20.2	22.3	23.8	28.2	38.8

An investigation of these values shows that, like the displacements of the hydrogen absorption lines, they vary in direct proportion to the wave-length. The residuals given by a least-squares solution assigning weights according to the number of measures are as follows:

	O−C
H_ϵ..............	−1.8
H_δ..............	−0.5
H_γ..............	−0.3
H_β..............	+1.2
H_α..............	+2.4

A similar relationship has been found by Professor Plaskett for the widths of the bright hydrogen bands.

4. THE HELIUM LINES

The helium and parhelium lines which can be identified with reasonable certainty in the *Nova* spectrum are given in the following list. The absorption lines accompanying the bright bands are also included, the more doubtful identifications being placed in parentheses.

CENTERS OF HELIUM LINES

He	Bright Band	Absorption Lines	
		I	II
4143.92	4146.4	(4133.4)	(4123.6)
4169.13	4173.1	......	......
4388.10	4387.4	......	......
4437.72	4438.4	(4429.5)	(4418.6)
4471.65	4473.2	4460.6	(4452.2)
4922.10	4925.9	4911.1	4900.6
5015.73	5019.5	5004.2	4994.7
5047.82	5048.7	......	......
5875.87	5878.0	......	......
6678.37	6677	......	......

In addition to these lines λ 4713.25 is probably present, at least upon the later photographs, but blended with a portion of the great band which extends from λ 4600 to beyond λ 4700. The average displacement of the bright bands toward the red is 2.1 Ångströms, or about the same as that of the hydrogen lines, but the measurements are much less accurate except in the case of λ 4926 and λ 5020, the bands being fainter and probably complicated with other bands in some cases. It seems probable that the displacements of both dark and bright lines are proportional to the wave-length.

Campbell and Wright in their discussion of the spectrum of *Nova Persei* have called attention to the interesting fact that on the earlier spectrograms of the star the parhelium lines are the ones observed, while in the later observations these have become very faint or have disappeared and the helium lines have become prominent. They refer to the observations of Runge and Paschen which indicate that with increase of pressure in the radiating gas the helium lines become stronger relatively to the parhelium lines. Of the lines listed in the table above as observed in *Nova Geminorum*, λ 4471, λ 4713, and λ 5875 belong to the helium series and the remainder to parhelium. The line λ 4471 was probably present upon the earliest photographs, but very faint. It was first measured by us on a spectrogram taken on April 6, and continuously throughout the series after that time. The line λ 4713 we have already referred to as probably being present upon the later photographs merged in another bright band. The D_3 line, λ 5876, is present on the spectrogram of March 28, but is considerably stronger upon the photograph of May 10. The parhelium lines, with the possible exception of λ 5048 and λ 6678, were much stronger upon the earlier photographs, although most of them could still be seen throughout the whole series. The line at λ 5016 was last measured on March 30. The two parhelium lines, λ 5048 and λ 6678, however, appear to be present only upon the later photographs, the former being first measured on the spectrogram of May 5, and the latter on May 10. In general the relative behavior of helium and parhelium lines seems to resemble their behavior in *Nova Persei*, but not to be identical with it.

5. NEBULAR LINES

The bands which are almost certainly identical with lines observed in the spectra of nebulae are indicated in Table I. In addition to hydrogen and helium they are as follows:

Nova		NEBULAE
Limits	Center or Maximum	
4062–4074	4068	4069
4259–4280	4270	4265
	4365	4363
	4579	4574
	4599	459
	4612	461
	4641	464
4674–4700	4687	4686
4954–4974	4960	4959
4993–5022	5007	5007
5743–5770	5757	5752
6288–6319	6303	6301

The line λ 4686 is the first line in the principal series of hydrogen. The three lines of the second subordinate series may perhaps be present in the *Nova* spectrum; they are known to be present in the spectra of Wolf-Rayet stars, and their wave-lengths as determined by us in the star *B.D.*+30° 3639 are added for comparison.

H	*Nova*	*B.D.*+30° 3639
4026	Band 4018–4052	4028
4201	Center faint band 4201	4201
4542	Violet edge bright band 4540	4542

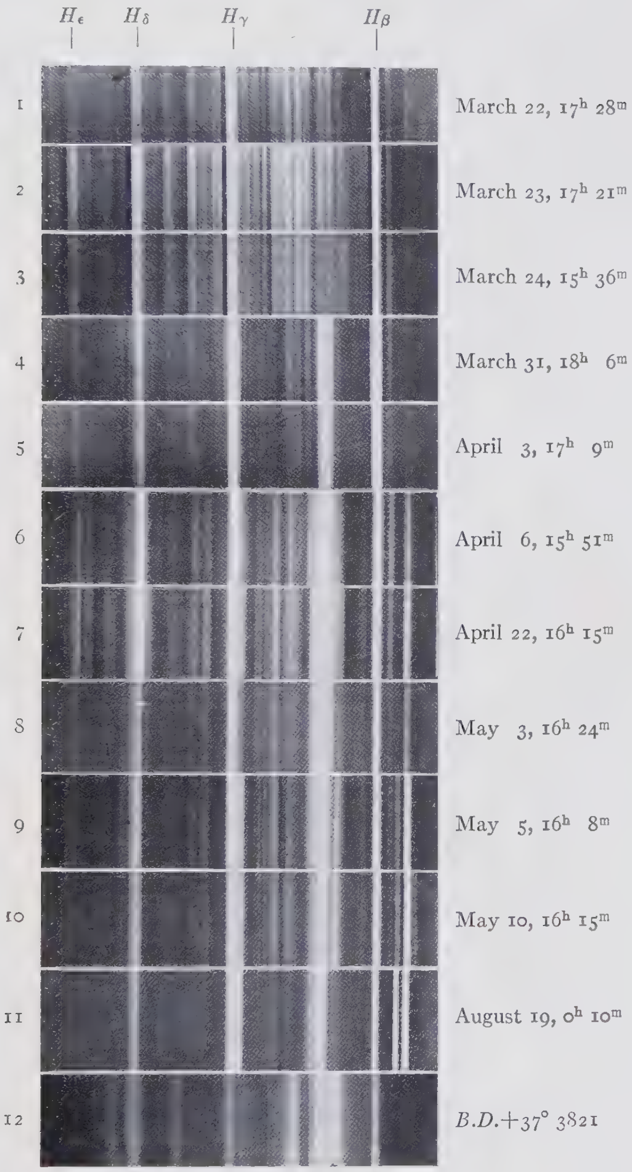
The spectrum of the *Nova* in its later stages and the spectra of Wolf-Rayet stars have numerous features in common. The greatest point of difference is, of course, the absence, or at least the comparative faintness, of some of the principal nebular lines in the Wolf-Rayet spectrum. Apart from this feature there is probably fully as much difference between spectra of individual stars of the Wolf-Rayet type as there is between the *Nova* and certain of these stars. For purposes of comparison the spectrum of the Wolf-Rayet star *B.D.*+37° 3821 is reproduced with the *Nova* spectra in Plate XVII. The most striking feature of the spectrum of this star is the great intensity of λ 4686 and the prominence of the three lines already referred to which belong to the second subordinate series of hydrogen, λ 4026, λ 4201, and λ 4542.

A comparison of the widths of the bright hydrogen bands in the spectrum of *B.D.*+37° 3821 and of the *Nova* gives the following results:

	Nova	*B.D.*+37° 3821
$H\delta$	λ 4092–4114	4081–4117
$H\gamma$	4330–4354	4325–4354
$H\beta$	4849–4876	4843–4877

Within the limits of error of measurement the red edges of the bands have the same position. The violet edges in the case of the *Nova* are affected by the presence of absorption which is absent in the case of the Wolf-Rayet stars. The violet edges, accordingly, differ by roughly the same amount in the two cases. It is clear, therefore, that in a type of spectrum which we are accustomed to

PLATE XVII



1–11 SPECTRA OF *Nova Geminorum* No. 2
12 SPECTRUM OF WOLF-RAYET STAR *B.D.*+37° 3821

consider as relatively permanent, emission bands of the same order of width are present as in the spectra of *Novae*. On the other hand, the hydrogen lines in the spectrum of the Wolf-Rayet star *B.D.*+30° 3639 are very narrow while other bands in the spectrum are as much as 20 Ångströms wide. This seems to us an objection to the hypothesis of Kayser that such bands may be due to the Doppler effect in gases under the bombardment of *Kanalstrahlen.*

In 1907 Hartmann made an important investigation of the spectrum of *Nova Persei* nearly six years after its discovery[1] and found its spectrum to resemble very closely that of the Wolf-Rayet star *B.D.*+35° 4001. *Nova Persei* at that time was of about the eleventh magnitude.

6. PROBABLE IDENTIFICATIONS

The sodium lines D_1 and D_2 appear as narrow absorption lines in a bright band whose red edge falls at λ 5910. On the violet side this band blends with the bright D_3 band of helium.

A faint bright band extending from λ 5160 to λ 5184 is probably due to the *b* group of magnesium. A maximum at λ 4480 in the bright helium band λ 4463–λ 4485 is probably due to magnesium λ 4481.

The H and K lines of calcium like the sodium lines are narrow absorption lines in broad bright bands. The bright band due to the K line extends from λ 3925 to λ 3949, while the H band is lost in that of the H_ϵ line. The K band is not seen after March 30. It seems very doubtful to us whether λ 4227 of calcium is represented in the *Nova* spectrum. This region is extremely complex and the bright band falling nearest the position of the line extends from λ 4224 to λ 4246 with a center at about λ 4235 on the earlier plates. On later photographs it seems to have even a longer wave-length, due probably to an extension of the band toward the red. The two absorption lines λ 4223.1 and λ 4213.9 probably belong to this band, and the wave-lengths of all three make it improbable that this can be due to calcium λ 4227.

A number of faint absorption lines present on the earliest plates may perhaps be identified with calcium. A number of these are given by Professor Küstner. Our own values are as follows:

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[1] *Astronomische Nachrichten*, **177**, 113, 1908.

Nova	Sun (Rowland)
λ 4282.1	4283.17
4302.8	4302.69
4307.3	4307.91
4459.0	4454.95
4580.7	4581.58
4587.0	4586.05
4685.9	4685.45

In view of the large number of dark lines present in the *Nova* spectrum these identifications seem to us of rather doubtful value.

A considerable number of the absorption lines may be identified with lines of iron, and several others with lines of titanium, particularly with enhanced lines of this element. The possible identifications are indicated in Table I.

In his discussion of the spectrum of *Nova Lacertae*[1] Mr. Wright has instituted an interesting comparison between the bright stellar bands and the lines of the spark spectrum of nitrogen. Other observers have noted a similarity between the spectra of Wolf-Rayet stars and the spectra of oxygen and nitrogen. If we compare the lines of nitrogen given by Wright with our measures of the bright bands of *Nova Geminorum* we obtain the list in Table II.

There is practically a continuous band in the *Nova* spectrum between λ 4600 and λ 4700, and the values given are the centers of subordinate bands or of maxima. The fainter lines of the nitrogen spectrum show about the same degree of agreement with the stellar bands. In view of the evidence we are inclined to consider the presence of nitrogen in *Nova Geminorum* as probable, although we would agree with Mr. Wright in considering it as hardly proven.

The announcement by Professor Küstner and Dr. Giebeler of the discovery of dark lines in the *Nova* spectrum due to radium and the radium emanation arrived while we were engaged in preparing our results for publication. Owing to the fact that our series of observations did not begin until March 22, or several days after the first observations at Bonn, the results are not fully comparable, especially in view of the very rapid changes in the spectrum at this time. As bearing on the question of the presence of radium absorption lines after March 22, however, the results may be of interest.

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[1] *Lick Observatory Bulletin*, No. 194, 1911.

TABLE II

Nitrogen Exner and Haschek and Neovius	Intensity	*Nova* Bright Bands
3995	50	Band 3986–4008
4026	3	Band 4018–4050
4035	4	Center 4035
4042	5	
4097	3	Conflict with H_δ
4103	3	
4146	4	Center band 4146 (*He?*)
4176	3	Center band 4173 (*He?*)
4207	2	
4229	3	Band 4224–4246
4237	5	Center 4237
4242	5	
4348	2	Conflict with H_γ
4426	2	Maximum 4425
4433	2	Band 4435–4450
4447	20	Center 4442
4508	2	Band 4508–4534
4515	1	
4530	2	
4601	5	Maximum 4600
4607	4	Center band 4605
4614	3	
4622	4	Center band 4622
4631	15	Center band 4632
4643	5	Center band 4641
4649	5	Center band 4649
5003	10	Band 4991–5032
5007	10	*He* 5016 and on later plate N_1 5007
5045	7	Conflict with *He* 5048
5497	6	
5535	6	
5667	9	Band 5667–5694
5680	12	Center 5681
5712	6	Red edge band 5711

In the region of spectrum considered by Giebeler there are 12 lines in the spark spectrum of radium for which he has found corresponding lines in the *Nova*. Of these we have been able to measure seven upon our photographs. Two of these, however, fall within the H_γ band and their agreement with radium lines is entitled to little significance on account of the presence of a great number of narrow dark lines, so many, in fact, that accidental coincidence would be almost certain. On two of the remaining five lines, λ 4153 and λ 4532, our measures show very close agreement with those of Giebeler and indicate discrepancies of over an Ångström unit from the radium lines.

In the region of wave-lengths longer than λ 4533 we find possible coincidences with λ 4600, λ 4642, λ 4693, and λ 4826. The first of these seems to be double in the *Nova* spectrum, and the discrepancy both for it and for λ 4826 is large. The extremely bright radium line λ 4683 does not appear to be represented in the *Nova*.

The degree of correspondence in the case of the emanation spectrum is about the same as for the radium spark, about 50 per cent of the lines having possible coincidences in the *Nova* spectrum. There are dark lines near the positions of the very intense lines λ 4167, λ 4350, λ 4609, and λ 4626, but none near λ 3982, λ 4203, and λ 4681. In general there seems to be very little agreement between the relative intensities of the emanation and the radium spark lines and the dark lines in the *Nova*, and the same fact seems to be true of Giebeler's results. Thus the four strongest radium lines (omitting λ 4341, which falls on the H_γ band) in the part of the spectrum investigated, λ 4178, λ 4305, λ 4436, and λ 4533, have been measured by him upon but one photograph, while several of the fainter lines have been measured more frequently.

In view of these results we do not consider the presence of the radium or the emanation spectrum in the *Nova* as established, at least for the period covered by our observations.

We have not been able to detect with any certainty evidence of a periodic variation in the structure of the bright hydrogen lines such as was suspected by Wolf,[1] but the dates of the observations

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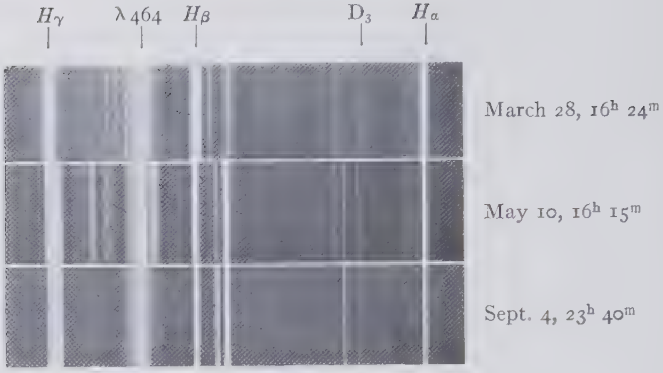
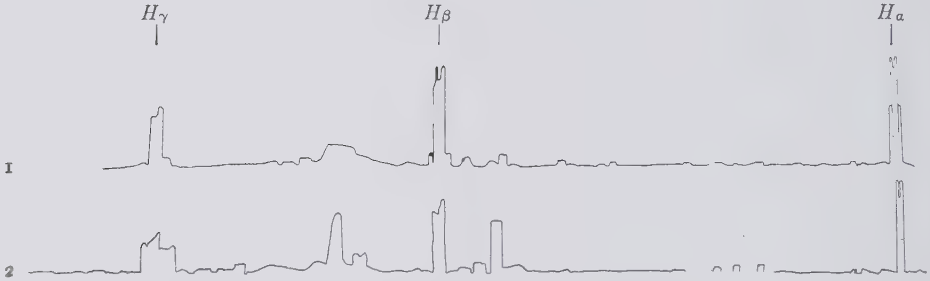
[1] *Astronomische Nachrichten*, **191**, 167, 1912.

PLATE XVIII



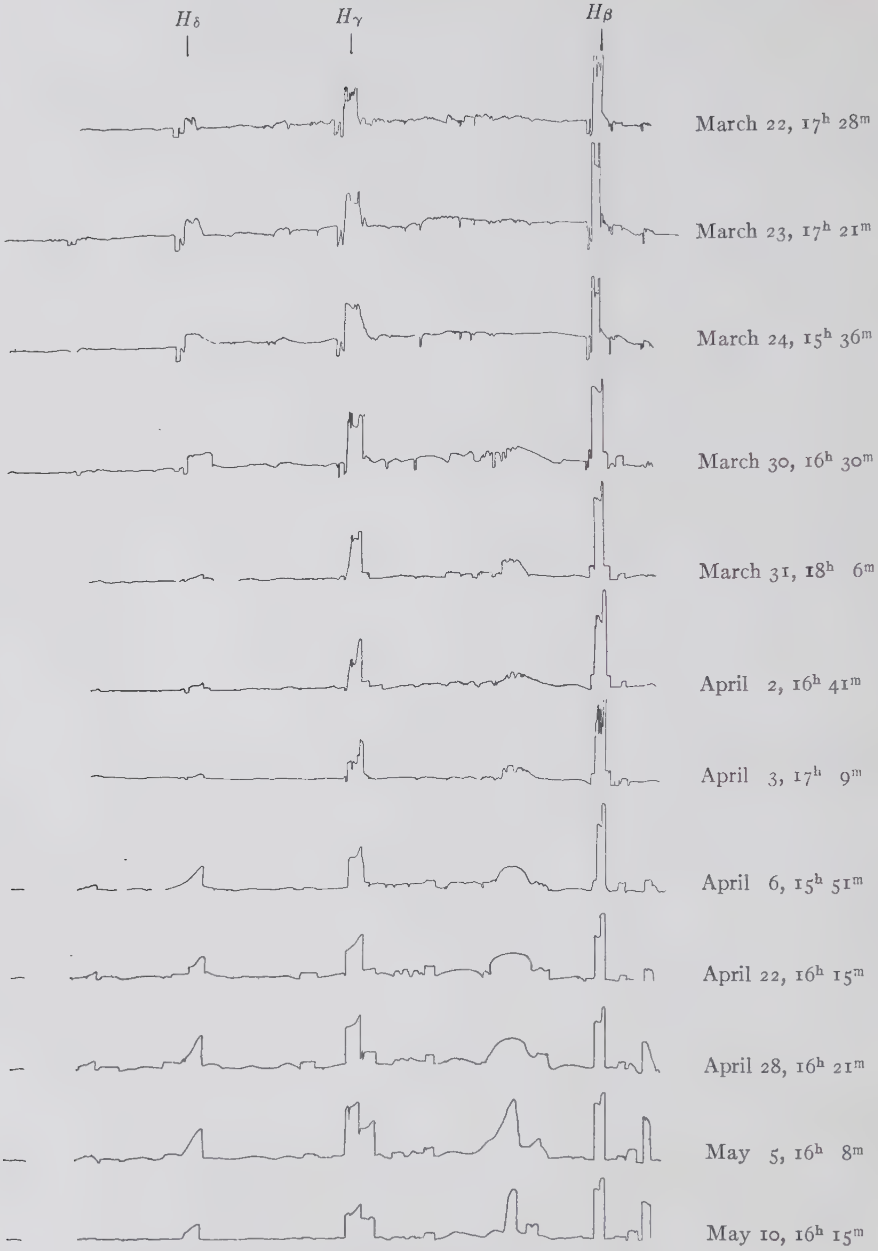
SPECTRA OF *Nova Geminorum* No. 2



INTENSITY CURVES OF SPECTRA OF *Nova Geminorum* No. 2

1. March 28, 16^{h} 24^{m}
2. May 10, 16^{h} 15^{m}

PLATE XIX



Intensity Curves of Spectra of *Nova Geminorum* No. 2

were not particularly favorable for such an investigation. It is perhaps worthy of note that there appears to be some evidence of a progressive change in the wave-lengths of the bright hydrogen bands during the period of rapid decrease in the light of the star, March 25–April 6. As the brightness grew less and the star more red in color the bands appeared to shift somewhat toward the red. It is possible that there may be a shift in the maximum of the individual bands with decrease of temperature similar to that found in a continuous spectrum.

The complex structure of the hydrogen bands led us to make an attempt to detect possible polarization in the spectrum of the star. Two spectrograms were obtained on April 7, using a Nicol prism and a quarter-wave plate in front of the slit. No displacement of the bright maxima was found when the quarter-wave plate was rotated. The dark hydrogen lines had become very faint at this stage of the development of the spectrum and are not visible on the photographs.

Since the above was written we have succeeded in obtaining two spectrograms of the *Nova* in the eastern sky. The first of these, γ 1472, was secured on August 19 and includes the portion of the spectrum between λ 4000 and λ 5000. The second, γ 1591, obtained on September 4, includes the entire spectrum from λ 4000 to H_α. On account of the low altitude of the star and the impossibility of giving a very long exposure because of the approach of daylight the second spectrogram was somewhat underexposed. Enlargements of the spectra are shown in Plates XVII and XVIII. The star appeared to be not far from the ninth magnitude at the time of these observations.

A comparison of these spectrograms with those obtained in the latter part of May indicates a further development of the spectrum of the star toward the nebular stage. The chief nebular line, λ 5007, is now considerably more intense than H_β, and similarly the nebular line at λ 4365 is stronger than H_γ. The second nebular line, λ 4959, and the line at λ 5757 have also increased greatly in intensity. On the other hand, the band at λ 4641 has become fainter and the principal series line of hydrogen at λ 4687 can hardly be distinguished at all. The helium lines λ 4472 and λ 5876 are of about the same intensity as on the earlier photographs.

In the accompanying table are given the results of our measures of some of the more important bands and lines on these spectrograms, together with the results obtained from the photographs taken in the latter part of May.

	γ 1472 −γ 1591	Width Ångströms	γ 1185 −γ 1201	Width Ångströms
H_ϵ	3970.1	15.3	......	....
H_δ	4102.5	22.9	4102.6	24.9
Nebular	4269.6	19.2	4269.4	20.7
H_γ and nebular	4351.1	45.6	(4353.3)	(47.7)
	4442.5	15.8	4443.0	14.0
Helium	4473.3	20.3	4473.8	22.0
Nebular	4639.5	38.9	4640.8	....
H_β	4862.6	25.7	4863.0	29.9
Nebular	4960.1	25.8	4960.1	27.8
Nebular	5007.9	28.5	5007.1	25.4
Nebular	5680.4	....	5680.2	27.2
Nebular	5757.4	26.3	5755.9	27.4
Helium	5878.2	....	5878.1	26.5
H_α	6566.5	35.8	6569.4	39.8

It is clear from this comparison that no very marked changes either in the wave-lengths or the widths of the bright bands have taken place in the interval of three months between the two series of observations. The widths of the bands are somewhat less on the later photographs, except in the case of one or two lines; but the difference is probably due in main to the fact that the density of the later negatives is less than that of the earlier series. In this respect, as has previously been stated, the bands resemble similar bright bands found in the spectra of Wolf-Rayet stars, and are widely different from the narrow sharp lines characteristic of the spectra of gaseous nebulae.

There appears to be a slight tendency toward a reversion to their normal wave-lengths of the centers of the bright bands, but the effect is too slight to be recognized with certainty. The marked change in the wave-length of H_α, and in a less degree of λ 5757, is due in all probability to the uncertainties of measurement in this part of the spectrum. A general displacement toward longer wave-lengths of the centers of the bands is still a characteristic of the spectrum, as it was in the earlier observations.

An important feature of the bright bands is the persistence of the faint broad absorption bands crossing them, which have been observed throughout the entire series of photographs. They appear to be symmetrically placed on the bright bands and are present on the nebular bands as well as on those of hydrogen and helium. In some cases they seem to be broken up into narrow lines such as were found upon some of the earliest photographs. The nature of the absorption is such as is characteristic of a thin layer of absorbing gas of considerable density.

We are indebted to Miss Lasby and Miss Ensign for many of the measures upon the spectrograms, and to Miss Burwell for the intensity-curves drawn from the original negatives. The enlargements of the spectra are due to Mr. Ellerman.

MOUNT WILSON SOLAR OBSERVATORY
September 23, 1912

Contributions from the Mount Wilson Solar Observatory, No. 63
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THE INTEGRATED SPECTRUM OF THE MILKY WAY

By E. A. FATH

In *Harvard Annals*, **56**, No. 1, is given a study of the distribution of the spectra of over 32,000 stars. Among other results are found: (1) That over 52 per cent of the stars investigated have A-type spectra; (2) The ratio of A-type stars to all other types increases as the brightness decreases; (3) In the Milky Way two-thirds of the stars investigated are of the A-type.

In view of these observations we might seem justified in drawing the following conclusions: (1) The integrated spectrum of our stellar system would be approximately of the A-type; (2) The integrated spectrum of the Milky Way as seen from our point of view would be of the A-type.

For some years the writer had planned to make a study of the integrated spectrum of some of the brighter regions of the Milky Way in order to test the validity of the second conclusion. An opportunity presented itself from March to June of last year, when Director Campbell of the Lick Observatory very kindly loaned the spectrograph which the writer had used for work on the Zodiacal Light. This instrument is described in *Lick Observatory Bulletin*, No. 165.

The region selected for the first trial was the very bright portion of the Milky Way partially bounded by the stars γ, δ, and λ *Sagittarii*, which is the brightest region of the galaxy seen at this latitude.

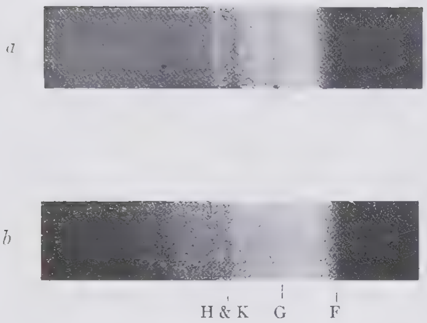
The method of observation was the simplest possible. The spectrograph alone was used, as the angular diameter of the surface investigated was greater than the angular aperture of the collimator lens. The instrument was mounted in such a way as to permit motion in azimuth and altitude. It was then pointed at the region in question and moved every 10 or 15 minutes to follow the diurnal motion.

The first exposure was begun on the night of March 30 and continued, whenever possible, until May 4. The total exposure on this first plate was 30^h20^m. As the spectrum obtained was not quite as strong as desired a second plate was taken in the interval from May 27 to June 29. The second exposure totaled 65^h13^m. It was of satisfactory intensity.

The general appearance of this spectrum is like that of the sun in that it shows the F, G, H, and K lines and three broad absorption bands to the violet of K. On closer examination, however, certain differences can be noted. There appears to be a bright line at 416 $\mu\mu$ and faint additional absorption lines at 411, 421, and 448 $\mu\mu$. The bright line is just halfway between the first two absorption lines. This raises the question as to whether it may not be merely a portion of the general continuous spectrum which appears especially strong by contrast. The line appears on both plates, while the three faint absorption lines appear only on the stronger of the two. The origin of these additional lines is uncertain. There is neither a bright auroral nor a bright nebular line in the neighborhood of the bright line observed. The absorption line at 411 $\mu\mu$ may possibly be H_δ; those at 421 and 448 $\mu\mu$ cannot be even approximately identified. These wave-lengths are probably uncertain by 1 $\mu\mu$ although for two entirely distinct sets of measures made over a week apart the greatest difference is 0.5 $\mu\mu$. This uncertainty is due in a large measure to the very small scale of the spectrum, for the distance on the plate between λ 5000 and λ 3900 is only 2 mm. The line at G is very broad and it is not impossible that H_γ may help in its formation.

It might be thought that the three stars, γ, δ, and λ *Sagittarii*, which are south and east of the star cloud under consideration and are of the K-type, have an injurious effect, but that this is not the case is shown by measures of the brightness of this region with a photometer of the type used by Yntema and described in *Groningen Publications*, No. 22. A provisional reduction of these measures gives the brightness of a square degree of the Milky Way in this very bright region equal approximately to 0.4 the light of a standard first magnitude star. The total intensity of the light of the three stars is equal to half that of a star of the first magnitude. The

PLATE XX



Integrated Spectrum of the Milky Way

a Spectrum of the Milky Way in *Sagittarius*. May and June 1911. Total exposure $65^h\ 13^m$. Slit, 0.8 mm.

b Spectrum of sky. Slit, 0.1 mm.

angular aperture of the collimator lens may be taken as 3°. Accordingly the area of sky affecting the plate at any time was about seven square degrees. Then, assuming the most unfavorable condition possible, namely, concentrating the light from the three stars into one at the center of the region, this would amount to less than one-fifth of the total light falling on the plate at any time. As a matter of fact, these stars could send no light whatever to the plate unless the spectrograph was not moved at sufficiently short intervals of time. This occurred a few times, as it was necessary to carry on this exposure at the same time the writer was observing with the 60-inch reflector, and time could not always be taken to make the required changes. Had the exposure been made, either by having the spectrograph moved by a driving-clock or by continuous motion of the alt-azimuth mounting by the observer, the light of the three stars would never have reached the plate.

This result was of sufficient interest to continue the work, the same spectrograph again being loaned by the Lick Observatory. The next plate was exposed a total of 67^h52^m during May and June 1912, on the bright region at $\alpha=18^h42^m$, $\delta=-8°$. This time the spectrograph was attached to the coelostat of the Snow telescope, a new set of gears providing the required speed of rotation. The plate is very much like the previous one, except that it is not quite so dense and the absorption line at 421 $\mu\mu$ is absent.

A third exposure was made during July and August 1912, on the region between β and η *Cygni*. This exposure amounted to 74^h11^m. The spectrograph was again attached to the coelostat of the Snow telescope.

The intensity of the last plate is about the same as that of the stronger plate of the *Sagittarius* region and the spectrum is similar in its general appearance, but the absorption line at 411 $\mu\mu$ is relatively stronger and the possible bright line at 416 $\mu\mu$ is relatively weaker.

The four plates taken of three bright portions of the Milky Way are therefore in agreement in indicating that *the integrated spectrum of the Milky Way is approximately of solar type.*

This result receives an independent check from a series of plates taken to test the possible selective absorption, or loss, of light in space. On the strength of the Harvard result that the greater portion of the Milky Way stars are of the A-type, and assuming that this result could be extended to the fainter stars, it appeared possible to test the hypothesis that the more distant, and therefore fainter, stars are redder than the nearer brighter ones.

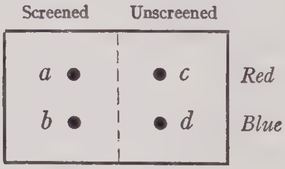
The regions selected for trial were centered at

$18^h30^m+10^\circ$	$18^h30^m+5^\circ$
18 40 +10	18 40 +5
18 50 +10	

and were photographed with the 60-inch reflector on red-sensitive plates.

On each plate two exposures of a region were made, one through a red and the other through a blue ray filter, the plate being moved a little in declination to separate the images of the two exposures. In addition one-half of the plate was kept covered by the slide of the plate-holder except during 30^s at the close of each 6^m of the exposure. Thus on the covered or "screened" half of the plate only the brighter stars are found. Accordingly it is possible to compare faint stars from the uncovered portion of the plate with bright stars from the screened portion.

The theory of the method which was suggested by Professor Kapteyn is as follows: Let us consider two stars, one from each half of the plate, at the same distance from the optical axis so that there will be no differential aberration effect, and with the red images approximately equal. Though these images are of the same size, that for the screened portion of the plate will be of a star approximately two magnitudes brighter, and hence, on the average, a less distant star, than that whose image lies within the unscreened portion.



On the assumption that there is a greater absorption and scattering of blue than of red light in interstellar space, the screened blue image b will be larger than the blue image d. Since all of the images compared are approximately of the same size the result will be free from photographic effects that might otherwise enter.

Let us put

$$a-c=m \tag{1}$$

$$b-d=n \tag{2}$$

On the basis of our assumption the value $n-m$ will be positive, that is

$$b-d>a-c$$

Subtracting (1) from (2)

$$(b-d)-(a-c)=n-m=\text{redness}=r$$
$$r=(b-a)+(c-d)$$

If r is positive the more distant stars are redder than those nearer at hand. Should r prove to be negative then the more distant stars are bluer.

The plates taken were measured in the following manner. A circle of 38 mm radius was drawn with its center at the center of the plate. No stars outside the circle were used on account of the large aberration beyond this limit. A star pair from the screened portion was then compared with any pair in the unscreened region that was approximately at the same distance from the center, the red images being as nearly as possible of the same size.

It will be unnecessary to go farther into the details of this matter. The result of the comparison of 76 pairs of stars on the five plates showed that, in the mean, the fainter stars are distinctly redder than the brighter ones. Had we been certain that the stars were all of approximately the same spectral type we should have strong evidence that the light from the fainter stars lost more of its blue than of its red component in traversing interstellar space, as compared with the brighter stars. The spectrograms, however, offer another explanation, namely, the ratio of A-type stars to other types decreases as the stars become fainter, and, from a certain undetermined magnitude on, the stars of approximately solar type predominate, so that the fainter stars, which give us the most of the Milky Way light, are in reality redder than the brighter ones. These two investigations are therefore in agreement, although the original purpose of the second is not served.

It is unfortunate that the regions selected for the second investigation were not identical with those of which spectrograms were obtained, but the former plates were taken first. It was not advisable to try a spectrographic exposure on these regions as they are too faint, the exposure required being probably in the neighborhood of 200 hours. The first spectrogram was obtained at about the same time as the other series of plates. The results of the latter were therefore not published in the form originally intended.

The Harvard investigation probably contains very few, if any, stars fainter than the 8th magnitude. Both the investigations discussed here deal almost exclusively with stars fainter than this. It would be a matter of interest to know at what magnitude the ratio of A-type stars to all other types reaches a maximum, as well as the magnitude at which the other types begin to predominate. From the material at hand, however, there seems to be no satisfactory method of obtaining these values.

In regard to the spectrographic exposures on the Milky Way it should be stated that every precaution was taken to prevent sunlight from any source reaching the plate. The exposures were not begun until the sky was thoroughly dark and were closed before dawn. Furthermore, no exposure was made while the moon was above the horizon.

In conclusion, the writer desires to express his great appreciation to Director Campbell of the Lick Observatory for the use of the spectrograph, and to Mr. P. J. Van Rhyn, who assisted in the exposure of the last plate.

Note added October 22.—The reproductions of the spectra are not very satisfactory owing to the enlargement required and the very coarse grain of the original negatives. In *a* the G-group is faintly indicated, H and K form a broad band, and the shadings to the left are the ultra-violet bands referred to above.

Mount Wilson Solar Observatory
August 27, 1912

Contributions from Mount Wilson Solar Observatory, No. 64
Reprinted from the *Astrophysical Journal*, Vol. XXXVI, pp. 368–384

THE *ALGOL* VARIABLE *RR DRACONIS*

By FREDERICK H. SEARES

Among the variable stars included in the program of observations carried on at the Laws Observatory was the object discovered by Madame Ceraski in 1904 which has since received the designation *RR Draconis*. When first placed on the observing-list the character of the variation was unknown, but the measures of the first two nights showed the star to be an *Algol* of unusual interest on account of the range and rapidity of its variation. It was found normally to be a little brighter than the tenth magnitude, but during the eclipses, which occur at intervals of two days and twenty hours, it became so faint as to disappear from view in the $7\frac{1}{2}$-inch equatorial with which the observations were made. The brightness at the time of disappearance was apparently a little less than the thirteenth magnitude, so that the range covered by the visual observations was in excess of three magnitudes, the average change being at the rate of nearly a magnitude per hour.

Though the nature of the variation during the two hours that the star remained invisible in the Laws Observatory equatorial could not be determined, it was possible from the steepness of the curve to derive the epochs of minima, and consequently the period, with precision. The photometer used was of the equalizing wedge type designed by Pickering,[1] and as the wedge itself had been carefully calibrated and tested[2] it was possible to reduce the measures to an absolute scale of magnitudes, which were then combined to form a mean light-curve. The details of the observations, which extended from June 29, 1905, to September 25, 1906, and their discussion were published in *Laws Observatory Bulletin*, No. 9. The elements found were

$$\text{Min.} = \text{J.D. } 2417026.682 + 2\overset{d}{.}831079\,E \quad \text{G.M.T.}$$

with an estimated uncertainty in the period of 1^{s}.

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[1] *Astrophysical Journal*, **13**, 249, 1901.

[2] *Laws Observatory Bulletin*, No. 7, 1905.

The light-curve derived from the visual observations, reduced to the zero point of the Harvard Polar Sequence in a manner to be described later, is given in Table I. The phase values in the first and third columns are counted from minimum. With the exception of a remark by Hartwig,[1] indicating a correction of $+20^{m}$ to the ephemeris derived from the above elements for 1911, no further results seem to have been published.[2]

TABLE I

Visual Light-Curve—Laws Observatory

Phase	Mag.	Phase	Mag.
$0^{d}.035$	12.96	$0^{d}.100$	10.51
0.040	12.58	0.110	10.35
0.045	12.29	0.120	10.23
0.050	12.02	0.130	10.13
0.055	11.79	0.140	10.03
0.060	11.59	0.150	9.95
0.065	11.40	0.160	9.88
0.070	11.23	0.170	9.82
0.075	11.08	0.180	9.77
0.080	10.94	0.190	9.74
0.085	10.81	0.200	9.72
0.090	10.70	0.210	9.71
0.095	10.60	0.220	9.70
0.100	10.51	0.230	9.70

In order to determine the total range and the character of the variation for the part of the curve not included in Table I, the star was followed photographically throughout the greater part of an eclipse on August 7, 1912, with the 60-inch reflector of the Mount Wilson Solar Observatory.

Eight plates including 61 exposures of 2^{m} each and 4 of 1^{m}, covering a period of six hours, were obtained; and on the following night three additional plates for the determination of the normal brightness of the variable and the zero point of the magnitude scale were made. The observational details are contained in Table II. On four of the plates exposures were made with various combinations of apertures for the purpose of establishing the magnitude scale of the comparison stars. For Nos. 784 and 785 the exposures with the full aperture alternated with those made with 32- and 14-inch diaphragms; for 790 the order of apertures was 60, 32, 14, 14, 32, and 60 inches; and for 791, 32, 9, 9, and 32 inches. Plate 792 was exposed both to the field of the variable and to the Pole, the order being, variable, Pole, Pole, variable.

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[1] *Vierteljahrsschrift der Astronomischen Gesellschaft*, **46**, 230, 1911. This correction and the ephemeris given by Hartwig are based on the provisional elements in *Laws Observatory Bulletin*, No. 9, p. 135. The final elements on p. 138 are more precise.

[2] The observations by Lehnert, *Astronomische Nachrichten*, No. 4596, arrived just as this paper was sent to the printer.

TABLE II

LIST OF PLATES

Date	G.M.T.	Plate No.	Exp. Time	No. Exp.	Aperture	Seeing
1912						
August 7....	$16^h 55^m$–$17^h 30^m$	778	2^m	9	60	5
	17 37 –18 16	779	2	8	60	4
	18 23 –19 1	780	2	8	60	3
	19 13 –19 47	781	2	9	60	3
	19 54 –20 29	782	2	9	60	2–3
	20 35 –21 11	783	2	9	60	2–3
	22 3 –22 37	784	2	9	60, 32	3
	22 42 –23 1	785	1	4	60, 14	3
August 8....	18 59 –19 11	790	1	6	60, 32, 14	5
	19 17 –19 30	791	2	4	32, 9	5
	19 34 –19 55	792	2	4	32	6

Fourteen comparison stars, all near the variable, were selected for use in the determination of the magnitude scale. The brightest of these, which is No. 1 of the list, is *B.D.*+62°1642, 9.3 mag. The others, all of which are fainter than the *Durchmusterung* limit, may be identified with the aid of the chart of the field shown in Fig. 1. On the diaphragm plates all of the comparison stars were measured. The resulting mean scale readings, corrected for distance error, are given in Table III. The subscripts in the headings of the table refer to the aperture. The mean scale readings of the stars of the Polar Sequence shown on plate 792 are also given in Table III, in the last column. The corresponding Polar Sequence numbers and magnitudes taken from *Harvard Circular*, No. 170, are in the two preceding columns. The scale readings for such stars as were used for the reduction of the remaining plates are given in Table V.

The data for plates 784–791 were reduced in the usual manner[1] for the determination of the magnitudes of the comparison stars. The various scales were brought to an arbitrarily chosen common zero point, and the separate values for the brightness of each star combined to form the provisional magnitude given in the second column of Table IV. The five columns immediately following contain the deviations of the separate determinations from the mean provisional magnitudes. There is no evidence of appreciable systematic differences between the different determinations of the scale, and in general the consistency of the results is satisfactory. The average deviation of a single magnitude, including the effect of scale error over a range of four magnitudes is 0.096 mag., which corresponds to a probable error of ±0.081 mag.

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[1] A general account of the methods of observation and reduction followed in photometric work with the 60-inch reflector is in preparation and will be published shortly.

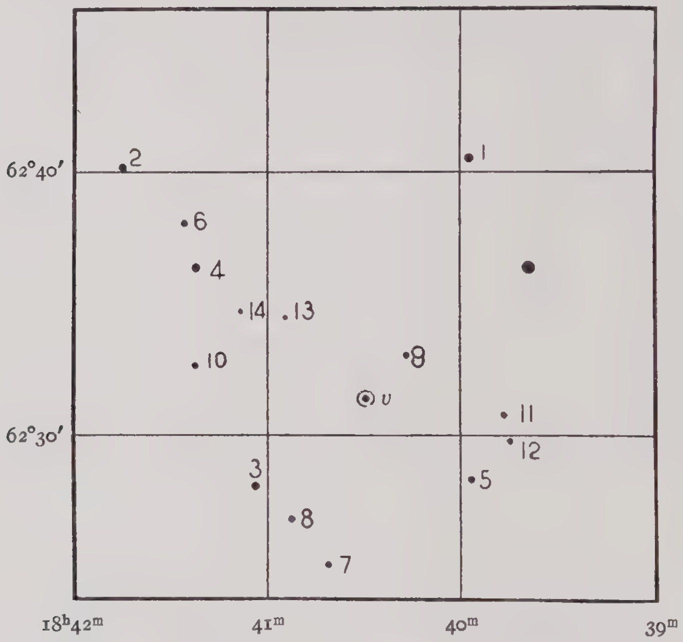

FIG. 1.—The comparison stars used with *RR Draconis* (1855.0)

To reduce the provisional magnitudes to the zero point of the Harvard Polar Sequence the values of the scale readings of the Polar Sequence stars given in Table III for plate 792 were plotted against the corresponding Polar Sequence magnitudes. From the curve thus established were read the values of the magnitudes corresponding to the scale readings of the comparison stars photographed on the same plate. These are entered in the eighth column of Table IV. The differences between these values and the corresponding provisional magnitudes in the second column appear in the ninth column and, disregarding extinction, represent separate determinations of the constant for the reduction of the provisional magnitudes to the Polar Sequence zero point. The interval of brightness covered by the polar stars is too short to afford a reliable comparison of the scale derived for the comparison stars with that of the Polar Sequence.

TABLE III

MEAN SCALE READINGS FOR MAGNITUDE SCALE PLATES

STAR	784		785		790			791		792			
											POLAR SEQUENCE		
	S_{60}	S_{32}	S_{60}	S_{14}	S_{60}	S_{32}	S_{14}	S_{32}	S_{9}	S_{32}	No.	Mag.	S_{32}
v . .	3.2	8.4	5.0	12.6	2.9	8.8	11.8	6.8	12.8	6.1	14	10.52	9.8
1 . .	3.3	8.5	5.0	12.6	3.6	9.0	12.2	7.3	13.3	6.6	7*r*	10.57	10.0
2 . .	. . . . .	13.8	10.9	. . . . .	. . . . .	15.5	. . . . .	14.2	. . . . .	13.7	5*s*	10.68	10.4
3 . .	9.3	14.3	11.4	. . . . .	9.4	15.6	. . . . .	14.1	. . . . .	14.3	18	11.92	14.4
4 . .	9.2	14.3	11.8	. . . . .	9.9	15.9	. . . . .	14.5	. . . . .	14.0	19	12.28	14.7
5 . .	9.3	14.6	12.2	. . . . .	10.9	17.8	. . . . .	14.6	. . . . .	14.7	7*s*	12.31	14.8
6 . .	10.4	15.8	12.2	. . . . .	11.8	. . . . .	. . . . .	15.5	. . . . .	16.3	20	12.59	16.6
7 . .	10.0	15.2	12.5	. . . . .	11.4	17.9	. . . . .	16.7	. . . . .	15.5	11*r*	12.87	18.5
8 . .	11.2	16.3	14.1	. . . . .	11.9	. . . . .	. . . . .	17.4	. . . . .	17.4			
9 . .	11.1	17.2	13.6	. . . . .	12.0	. . . . .	. . . . .	17.6	. . . . .	17.8			
10 . .	11.6	17.6	13.6	. . . . .	12.1	. . . . .	. . . . .	17.4	. . . . .	17.8			
11 . .	11.5	. . . . .	13.9	. . . . .	13.6	. . . . .	. . . . .	. . . . .	. . . . .	18.0			
12 . .	12.5	. . . . .	14.8	. . . . .	14.3	. . . . .	. . . . .	. . . . .	. . . . .	. . . . .			
13 . .	13.6	. . . . .	15.5	. . . . .	14.7	. . . . .	. . . . .	. . . . .	. . . . .	. . . . .			
14 . .	13.9	. . . . .	15.4	. . . . .	15.1	. . . . .	. . . . .	. . . . .	. . . . .	. . . . .			

The zenith distance of the variable for the mean time of exposure of plate 792 was 34°9. That of the Pole is 55°8. The difference is greater than desirable, but could not be avoided without a serious disarrangement of the observing program. In the absence of special extinction tables for Mount Wilson an approximate value of 0.20 mag. has been derived from those of Müller.[1]

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[1] *Photometrie der Gestirne*, p. 515, 1897.

The visual extinction has been doubled, and a rough interpolation has been made for elevation above sea-level. The application of the extinction correction to the mean of the quantities in the ninth column of Table IV gives for the reduction constant of the provisional magnitudes 8.95 mags. The resulting magnitudes adopted for the comparison stars are printed in the last column of Table IV.

TABLE IV

MAGNITUDE OF COMPARISON STARS

Star No.	Provisional Mag.	Residuals					Mag. from Polar Plate 792	Red. to Polar Sequence	Adopted Mag.
		784 60–32	785 60–14	790		791 32–9			
				60–32	60–14				
1	0.90	+1	+17	−11	−13	+6	....	....	9.85
2	3.03	+5	+1	+2	....	−7	11.87	8.84	11.98
3	3.12	−12	−10	+8	+11	+5	12.07	8.95	12.07
4	3.23	+1	−14	+5	+5	+3	11.98	8.75	12.18
5	3.40	+10	+7	−23	−12	+17	12.20	8.80	12.35
6	3.68	−3	+15	−16	−14	+16	12.53	8.85	12.63
7	3.70	+15	+5	−2	+2	−21	12.38	8.68	12.65
8	4.02	+8	−25	+15	+17	−12	12.70	8.68	12.97
9	4.03	−5	−5	+13	+14	−18	12.76	8.73	12.98
10	4.06	−18	−2	+13	+14	−8	12.76	8.70	13.01
11	4.28	+16	+9	−11	−15	....	12.80	8.52	13.23
12	4.58	+10	+3	−2	−9	....	....	....	13.53
13	4.80	−7	−2	+7	0	....	....	....	13.75
14	4.89	−9	+11	+4	−5	....	....	....	13.84
Means	....	0.086	0.090	0.094	0.101	0.113	....	8.75	
Extinction								0.20	
								8.95	

With the magnitudes of the comparison stars once established, the determination of the brightness of the variable becomes a simple matter. It is only necessary to plot the scale readings of the comparison stars for any plate against the adopted magnitudes and then read from the resulting curve the magnitude corresponding to the scale reading of the variable.

The scale readings for the comparison stars derived from plates 778–783 and given in Table V are the means of the eight or nine exposures on each of these plates, a single estimate with the photometric scale being made for each image. The results for the variable from these plates are given separately for each image in Table VI. These are the means of three estimates with the scale.

Since the mean image was used for the comparison stars, and separate images for the variable, it was necessary to correct the scale readings of the variable for the systematic deviations of the various exposures from the mean of them all. The corrections were derived by subtracting for each star the scale reading of each image from the mean scale reading for all the images of the star. The average of the differences for the same exposure for all the stars gives the correction which will reduce the scale readings for that exposure to the mean exposure for the plate. The results for the various exposures on the different plates are given in Table VII, the unit being 0.1 of a scale interval.

TABLE V

MEAN SCALE READINGS OF COMPARISON STARS

Star No.	Mag.	778	779	780	781	782	783
1......	9.85	4.1	.....	.....	.....	3.9	3.7
2......	11.98	9.2	.....	.....	.....	8.8	8.0
3......	12.07	10.6	.....	.....	.....	9.7	9.3
4......	12.18	10.4	.....	.....	10.7	11.0	10.7
5......	12.35	10.3	.....	.....	10.3	10.0	9.4
6......	12.63	11.0	.....	.....	11.6	.....	.....
7......	12.65	11.3	.....	.....	11.1	.....	.....
8......	12.97	12.0	12.1	11.8	12.0	.....	.....
9......	12.98	11.7	12.0	11.7	12.0	.....	.....
10......	13.01	12.3	12.7	12.3	12.3	.....	.....
11......	13.23	12.0	12.1	11.8	11.9	.....	.....
12......	13.53	.....	13.0	12.7	12.9	.....	.....
13......	13.75	.....	14.2	14.2	14.2	.....	.....
14......	13.84	.....	14.1	14.1	14.1	.....	.....

The corrections are in all cases small and show that the atmospheric conditions, both as to transparency and steadiness, were satisfactorily constant. The mean values in the last column give a pretty clear indication that the plates are free from the photographic effect which sometimes causes the first of a series of exposures on a plate to be systematically brighter than the last.[1]

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[1] Professor Pickering kindly allows me to quote from a personal letter as follows: "When several exposures are made on a plate, the first and last being short and equal, the images formed by the first exposure are almost always brighter than those formed by the last. The average difference is about a quarter of a magnitude."

The scale readings of the variable in Table VI are the corrected values. In the case of plates 784 and 785 the rate of change in the variable is so small that the mean scale reading of the various exposures is used, the only distinction being a separation of the results for the different apertures. The seventh column of Table VI contains the values of the brightness of the variable read from the magnitude curves for the various plates. The results are also shown graphically in Fig. 2.

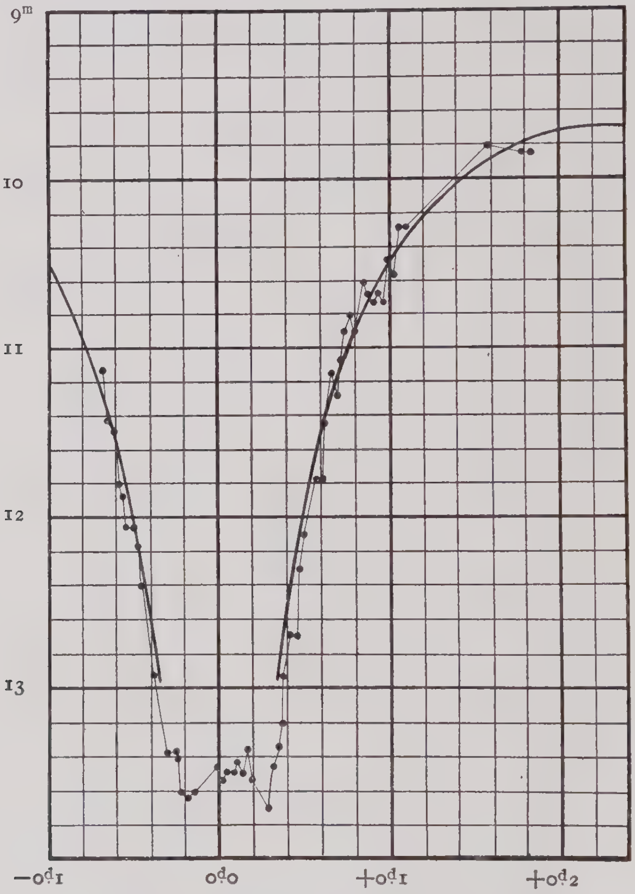

Fig. 2.—Light-curve of *RR Draconis* at eclipse

Broken line—Photographic observations
Full line—Laws Observatory visual light-curve

TABLE VI

MEAN SCALE READINGS AND MAGNITUDES OF *RR Draconis*

1912, August 7 and 8

Plate	Exposure	G.M.T.		Phase	*s*	Mag.	Phot.—Vis.
778.....	1	$16^h 56^m$	$0^d.705$	$-0^d.068$	7.3	11.12	−18
	2	17 1	0.709	−0.064	8.1	11.43	− 1
	3	5	0.712	−0.061	8.2	11.49	− 6
	4	9	0.714	−0.059	9.0	11.80	+16
	5	13	0.717	−0.056	9.2	11.88	+14
	6	17	0.720	−0.053	9.6	12.05	+17
	7	21	0.723	−0.050	9.6	12.05	+ 3
	8	25	0.726	−0.047	9.9	12.16	− 2
	9	29	0.728	−0.045	10.5	12.40	+11
779.....	1	17 38	0.735	−0.038	11.8	12.91	+18
	2	51	0.744	−0.029	13.0	13.37	−13*
	3	55	0.746	−0.027	13.0	13.37	−13
	4	59	0.749	−0.024	13.1	13.41	− 9
	5	18 3	0.752	−0.021	13.6	13.60	+10
	6	7	0.755	−0.018	13.7	13.63	+13
	7	11	0.758	−0.015	13.6	13.60	+10
	8	15	0.760	−0.013	13.6	13.60	+10
780.....	1	18 32	0.772	−0.001	13.1	13.46	− 4
	2	36	0.775	+0.002	13.3	13.53	+ 3
	3	40	0.778	+0.005	13.2	13.49	− 1
	4	44	0.781	+0.008	13.2	13.49	− 1
	5	48	0.784	+0.011	13.0	13.43	− 7
	6	52	0.786	+0.013	13.2	12.49	− 1
	7	56	0.789	+0.016	12.8	13.35	−15
	8	19 0	0.792	+0.019	13.3	13.53	+ 3
781.....	1	19 14	0.802	+0.029	13.8	13.70	+20
	2	18	0.805	+0.032	13.1	13.45	....
	3	22	0.808	+0.035	12.8	13.33	+37
	4	26	0.810	+0.037	12.5	13.20	+39
	5	30	0.812	+0.039	11.9	12.93	+27
	6	34	0.815	+0.042	11.4	12.69	+23
	7	38	0.818	+0.045	11.4	12.69	+40
	8	42	0.820	+0.047	10.5	12.30	+12
	9	46	0.823	+0.050	10.1	12.10	+ 8
782.....	1	19 55	0.830	+0.057	8.9	11.78	+ 7
	2	59	0.832	+0.059	8.9	11.78	+15
	3	20 4	0.836	+0.063	8.0	11.44	− 4
	4	8	0.839	+0.066	7.2	11.14	−23
	5	12	0.842	+0.069	7.6	11.29	+ 3
	6	16	0.844	+0.071	7.0	11.06	−14
	7	20	0.847	+0.074	6.6	10.90	−21
	8	24	0.850	+0.077	6.4	10.81	−21
	9	28	0.852	+0.079	6.6	10.90	− 7
783.....	1	20 36	0.858	+0.085	6.6	11.00	+19
	2	40	0.861	+0.088	5.8	10.68	− 6

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* The residuals for the phase values $-0^d.03$ to $+0^d.03$ refer to the minimum *photographic* brightness of 13.50 mags.

TABLE VI—*Continued*

Plate	Exposure	G.M.T.		Phase	*s*	Mag.	Phot.—Vis.
783.....	3	20^h44^m	0^d864	$+0^d091$	5.9	10.72	+ 4
	4	48	0.867	+0.094	5.8	10.68	+ 6
	5	52	0.870	+0.097	5.9	10.72	+16
	6	56	0.872	+0.099	5.3	10.48	− 5
	7	21 0	0.875	+0.102	5.5	10.56	+ 8
	8	6	0.879	+0.106	4.8	10.28	−13
	9	10	0.882	+0.109	4.8	10.28	− 9
784.....	60	22 20	0.931	+0.158	3.2	9.81	− 8
	32	20	0.931	+0.158	8.4	9.81	− 8
785.....	60	22 51	0.952	+0.179	5.0	9.85	+ 7
	14	54	0.954	+0.181	12.6	9.85	+ 8
790.....	60	19 5	1.796	+1.023	2.9	9.61	− 9
	32	5	1.796	+1.023	8.8	9.78	+ 8
	14	5	1.796	+1.023	11.8	9.71	+ 1
791.....	32	19 23	1.808	+1.035	6.8	9.69	− 1
	9	23	1.808	+1.035	12.8	9.69	− 1
792.....	32	19 44	1.822	+1.049	6.1	9.70	0

A curious fact is brought to light by the magnitude curves for plates 778–783 drawn from the data in Table V, namely, that although the adopted magnitudes afford a consistent representation of the measures of plates 784–791 as shown by the residuals in Table IV, they do not represent satisfactorily the scale readings for plates 778–783. This is clearly shown by the residuals in Table VIII which are the deviations for these plates of the adopted magnitudes from those corresponding to the observed scale readings, the latter being read directly from the curves. These residuals are clearly systematic, not in the sense that would indicate an error of scale, but as though the comparison star magnitudes were affected with large accidental errors. Most of the stars, for example, show deviations of the same sign and of the same order of magnitude for all of the plates of this group upon which they were measured. The difficulty is not with the comparison stars, however, but with the plates of this particular group for which the error depending on the distances of the stars from the axis of the instrument was undoubtedly abnormal. It has been found that comparatively small temperature deformations of the mirror are sufficient to modify radically the character and amount of the correction required to compensate this error. The mirror is known to have been in an abnormal condition during the early part of the night when the plates in question were exposed, but as it is impossible to determine the distance error for each plate separately, the correction for normal figure was applied. The systematic deviations in Table VIII represent the uncertainty of such a method of procedure. The comparison star magnitudes were derived from plates made after the mirror had become normal, or nearly so. That they are not also affected by an uncertainty in the distance error is shown by forming a similar table of deviations for the results obtained with the 32-inch diaphragm on plates 784, 790, 791, and 792. With this aperture the distance error is vanishingly small for the extent of field covered. The comparison of the adopted magnitudes with the scale readings for the diaphragm exposures should therefore reveal any uncertainty that may have entered through the full aperture exposures on the plates from which the magnitudes were derived. The resulting deviations are wholly accidental, however, from which we may conclude that the comparison star magnitudes are unaffected by a residual distance error.

The whole question of the determination of the proper correction to be applied for distance error is one that has given much trouble in photometric work with the 60-inch reflector. With care, however, the difficulties can largely be avoided, as will appear from a detailed discussion to be published in a later paper.

In the present case the matter is complicated by the fact that there is available but a single bright comparison star. Owing to the absence of other stars of similar brightness the magnitude curves were naturally drawn *through* the points corresponding to the bright star. For this reason no residuals appear in Table VIII for this object. The brighter magnitudes of the variables may therefore be slightly in error in such a way as to affect systematically the results for a plate; but only plates 782 and 783 can be so affected, and the smoothness of the resulting light-curve indicates that the errors must be small. The images of the variable itself are unaffected, as they were always near the axis. The results for normal light are also unaffected by residual distance error, for they were derived from plates made when the figure of the mirror was satisfactory, and depend almost exclusively upon exposures with diaphragms of 32, 14, and 9 inches for all of which the distance correction is negligible.

TABLE VII

REDUCTION TO MEAN EXPOSURE

Unit = 0.1 Scale Interval = 0.035 Mag.

Exposure	778	779	780	781	782	783	784	Means	
								s	Mag.
1.....	0	+2	...	+1	−4	+1	0	0.00	0.00
2.....	+1	...	+1	+1	−2	+3	+1	+0.08	+0.03
3.....	−1	−3	+3	+2	−3	+1	+3	+0.03	+0.01
4.....	+2	−2	+4	−1	−1	+3	0	+0.07	+0.02
5.....	+2	−1	−1	−1	+2	−7	−2	−0.11	−0.04
6.....	+2	0	−1	−3	+1	+2	0	+0.01	0.00
7.....	−1	+1	−2	+1	+2	−4	−1	−0.06	−0.02
8.....	−1	+1	−1	−3	0	+3	−1	−0.03	−0.01
9.....	−3	+1	−1	+2	+3	0	−2	0.00	0.00

TABLE VIII

COMPARISON STAR RESIDUALS

Star No.	778	779	780	781	782	783
1..........	....	....	....	....	....	....
2..........	−10	....	....	....	−23	−43
3..........	+36	....	....	....	0	0
4..........	+18	....	....	+20	+50	+43
5..........	− 2	....	....	−17	−15	−24
6..........	0	....	....	+17	....	....
7..........	+ 5	....	....	−12	....	....
8..........	+ 3	+ 6	+ 6	0	....	....
9..........	−10	+ 1	0	− 1	....	....
10..........	+13	+25	+19	+10	....	....
11..........	−22	−20	−20	−31	....	....
12..........	....	−16	−20	−16	....	....
13..........	....	+ 7	+ 6	+ 8	....	....
14..........	....	− 7	− 7	− 4	....	....

From a comparison of the times corresponding to a series of points on the steepest parts of the two branches of the light-curve the observed time of minimum is found to be 18^h33^m G.M.T. As the reduction to the sun is $+1^m$,[1] the observed heliocentric minimum is 1912, August 7, 18^h34^m G.M.T. with an uncertainty of 1^m. The minimum calculated from the original elements given above is $18^h45^m.2$. The correction to the ephemeris is therefore $-11^m.2$. As 917 periods separate the present minimum from the epoch of the elements, the correction to the period is $-0^s.74$ or $-0^d.000009$. The revised elements are therefore

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[1] *Laws Observatory Bulletin*, No. 9, 135, 1907.

$$\text{Min.} = \text{J.D. } 2417026.682 + 2^d.831070 \text{ E} \quad \text{G.M.T.}$$

with an uncertainty in the period of $0^s.07$.

From the last three plates listed in Table VI, all of which were exposed during normal light, the maximum brightness of the variable was found to be 9.70 mags. The result of the Laws Observatory visual observations, referred to the system of the Potsdam *Durchmusterung*, was 9.98 mags.,[1] which was obtained by a reference to stars 9950 and 10372 of the *Generalkatalog* whose colors are respectively GW and WG−. The spectrum of the variable is apparently of the A-type;[2] and though its exact classification is doubtful, there can be no question but that it belongs among the white stars. It is not likely therefore that the reference of the variable to the *P.D.* stars is greatly affected by color difference. The mean reduction of the two Potsdam stars to the system of the Harvard Observatory is −0.22 mag.[3] The normal brightness derived from the visual observations, referred to the Harvard system, is therefore 9.76 mags. The determination of this quantity depends upon the measurement with the equalizing wedge photometer of intervals of 2.9 and 2.4 mags.,[4] and the close agreement of the visual and photographic results indicates a satisfactory accordance of the visual and photographic magnitude scales. Further data bearing on this point will appear later.

The phase values in the fifth column of Table VI were obtained by subtracting the observed time of geocentric minimum from the epochs of observation in column four. Assuming that the interval of constant minimum light falls within the phase limits $\pm 0^d.030$, there are available for the determination of the minimum brightness sixteen observations. The mean result is 13.50 mags. The inclusion of the first three observations is questionable, though the symmetry of the curve indicates that they fall within the period of constant light. If excluded, the minimum brightness becomes 13.53 mags.

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[1] *Op. cit.*, p. 128.

[2] *Annals Harvard College Observatory*, **56**, 189.

[3] *Publikationen des Astrophysikalischen Observatoriums zu Potsdam*, **17**, XXXIV, 1907.

[4] *Laws Observatory Bulletin*, No. 9, 128, 1907.

The ordinate of the visual light-curve for normal light, referred to the star *B.D.*+62°1639, is +0.34 mag.[1] As the normal brightness has been found to be 9.70 mags., the visual curve may be reduced to the zero point of the Polar Sequence by adding to its ordinates the constant 9.36 mags. The values given in Table I were derived in this manner, and the corresponding curve is shown with the photographic observations in Fig. 2. The values of the deviations in hundredths of a magnitude appear in the last column of Table VI. Within the phase limits $\pm 0\overset{d}{.}030$ for which the visual curve is lacking, the residuals are referred to the minimum photographic brightness.

It will be noted that for two magnitudes below normal light the photographic variation is closely represented by the visual light-curve. From this point on, the photographic variation is greater than the visual, the divergence amounting to about three-tenths of a magnitude in an interval of a magnitude and a half. If it be assumed that the photographic and visual range of variation are necessarily the same, this would imply a relative error in the photographic and visual scales of 20 per cent; but in view of their close agreement for the first two magnitudes of the light-change and for the intervals measured in determining the normal brightness referred to above this is unlikely, and the evidence, as far as it goes, indicates that the photographic range is really greater than the visual. For the greater part of the curve the variation is rapid, and the last magnitude of the change requires but twenty minutes.

The value of the range of variation given by the photographic observations is 3.80 mags. As to the reliability of this result, the following may be remarked: The uncertainty of the values for both maximum and minimum brightness of the variable as indicated by the deviations of the individual values from the means is only 0.02 mag. The actual uncertainty for maximum light is considerably in excess of this, however, owing to the fact that there is but one comparison star at all comparable in brightness with the variable. Any error in the brightness of this star will therefore enter practically to its full value into the calculated brightness of the variable. The comparison star residuals in Table IV indicate that the uncertainty for the object in question, No. 1, is ±0.04 mag., which includes the effect of scale error, but not that of the zero point. For minimum light on the other hand the course of the magnitude curves from which the brightness of the variable was read is determined by several comparison stars, so that, disregarding again the error of the zero point, the uncertainty entering through the comparison stars into the minimum brightness is comparatively small. From a consideration of these points it seems likely that the observed range in brightness is correct within a tenth of a magnitude, unless there is an unsuspected error affecting similarly all of the separate determinations of the magnitude scale.

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[1] *Op. cit.*, p. 136.

So far as the amount of variation is concerned *RR Draconis* stands third among the 134 variables listed in *Harvard Annals*, **56**, 187. It is exceeded only by *RW Tauri*, for which the range is 3.9 mags., and by *RZ Aurigae*, to which a photographic amplitude of 5.0 mags. is assigned, though the visual variation is much less, the results by various observers being 2.1[1] and 1.7 mags.[2]

Though it is not at present desirable to enter upon a detailed investigation of the system, certain points may be noted. The observed eclipse is, of course, that of a bright object by one relatively faint, for such is always the character of the eclipse corresponding to a principal minimum. Moreover, the data are sufficient to show that the eclipse is total and not annular—that the darker star is the larger of the two.

If λ_p and λ_s represent the light received during the principal and secondary minima, respectively, and if k be the ratio of the diameter of the smaller star to that of the larger, we have[1] when the principal minimum is the total eclipse,

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[1] Hartwig, *Astronomische Nachrichten*, **178**, 395, 1908.

[2] Pračka, *ibid.*, **185**, 291, 1910.

$$\lambda_s = 1 - k^2\lambda_p \tag{1}$$

and when the principal minimum is the annular eclipse

$$\lambda_s = \frac{1-\lambda_p}{k^2} \tag{2}$$

Corresponding to the range 3.80 mags. $\lambda_p = 0.03$, whence (1) and (2) become, respectively,

$$\lambda_s = 1 - 0.03k^2 \text{ (Prin. Min. is Total Ecl.)} \tag{3}$$

$$\lambda_s = \frac{0.97}{k^2} \text{ (Prin. Min. is Annular Ecl.)} \tag{4}$$

subject to the condition $\lambda_s < 1$. Equation (3) is obviously possible, but in order that (4) may exist we must have $k^2 > 0.97$.

From the general relations for a circular orbit of inclination i

$$\frac{(1-k)^2}{(1+k)^2} = \frac{\cot^2 i + \sin^2 \theta_2}{\cot^2 i + \sin^2 \theta_1} \tag{5}$$

in which θ_1 and θ_2 are the longitudes of the smaller star, counted from minimum, corresponding to the first and second contacts of eclipse, that is, to the beginning of the variation and of the constant minimum phase. Since i is necessarily nearly 90° we may write (5) in the form

$$\frac{1-k}{1+k} = \frac{\sin \theta_2}{\sin \theta_1} \tag{6}$$

and derive an approximation for k from

$$k = \frac{\sin \theta_1 - \sin \theta_2}{\sin \theta_1 + \sin \theta_2} \tag{7}$$

This value will in general be too large; for since $\sin \theta_1 > \sin \theta_2$, the true value of $(1-k)/(1+k)$ from (5) will be larger than that given by (6), and hence the true k will be *less* than the approximation from (7). If therefore the value of k from (7) is such that $k^2 < 0.97$, there is no possibility of the principal minimum corresponding to annular eclipse. Such in fact is the case, for the phase values of the first and second contacts are $0\overset{d}{.}22$ and $0\overset{d}{.}03$, respectively. From these we find from (7) for the maximum value of k, 0.76, and of k^2, 0.58, which is far below the limit corresponding to the association of the annular eclipse with the principal minimum. The estimation of the times of contact is naturally very uncertain, but even if we assume such extreme values for the phases as $0\overset{d}{.}30$ and $0\overset{d}{.}015$ the result for the maximum k^2 is 0.81, which is still safely below the limit. Such phase values are, however, clearly excluded by the observational data, and we can only conclude that the eclipse corresponding to the principal minimum is total. The system is therefore remarkable in that the smaller of the two stars is the brighter.

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[1] Russell, "On the Determination of the Orbital Elements of Eclipsing Variable Stars," *Astrophysical Journal*, **35**, 323, 1912.

This result strengthens the conclusion stated above as to the probability of the photographic range being in excess of the visual. In fact with such a system the photographic range must almost certainly be greater than the visual, for, since the fainter body is the larger, the chances are very strongly in favor of its being redder than the brighter. During normal brightness the light is preponderatingly that of the brighter star, which is of the A-type, and the photographic and visual magnitudes will be sensibly the same. During the principal minima the A-type star is wholly eclipsed by its larger and redder companion. As the latter is fainter photographically than visually, the photographic range of variation must be greater than the visual. Moreover, for a large part of the light-curve there will be no appreciable difference between the photographic and the visual magnitudes, for the relatively small amount of light emitted by the darker star will not form any considerable portion of the total received until the eclipse is well under way.

Finally it may be noted that equation (3) shows that the light during the secondary minimum can scarcely be less than 0.98, which corresponds to an amplitude of only 0.02 mag.

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ON THE OCCURRENCE OF THE ENHANCED LINES OF TITANIUM IN ELECTRIC FURNACE SPECTRA

By ARTHUR S. KING

In the course of an investigation now in progress on the variations in the spectrum of titanium given by different temperatures of the electric furnace, it seemed highly desirable to make a special effort to obtain the enhanced lines and fix their place, if possible, on a temperature scale. In general, enhanced lines are very difficult to produce in the furnace, as is to be expected from the fact that for most metals they appear in the arc only under special conditions, either close to the poles or in an interrupted arc which gives momentary conditions approaching those of the spark. However, the arc shows these lines for some substances much more easily than for others. Thus, the H and K lines of calcium, which are to be classed as enhanced lines, are also among the strongest arc lines. It was shown in a previous paper[1] that they may be obtained in the furnace at a stage considerably below the highest furnace temperatures, and exhibit a rapid rise in intensity with temperature. The enhanced lines of titanium also occur in the arc, some of them being fairly strong, though weaker than many of the arc lines. It has been shown in previous publications[2] that the furnace at high temperatures gives a spectrum for titanium comparing in richness with that of the arc, but the enhanced lines were notably lacking in the furnace. Their strength in the arc, however, gave promise that by forcing the furnace temperatures the enhanced lines could be made to appear. This has been accomplished, and some supplementary experiments have shown several remarkable phenomena bearing directly on the nature of enhanced lines in general which will be reported in this paper.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 32; *Astrophysical Journal*, **28**, 389, 1908.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908; *Contributions from the Mount Wilson Solar Observatory*, No. 60; *Astrophysical Journal*, **35**, 180, 1912.

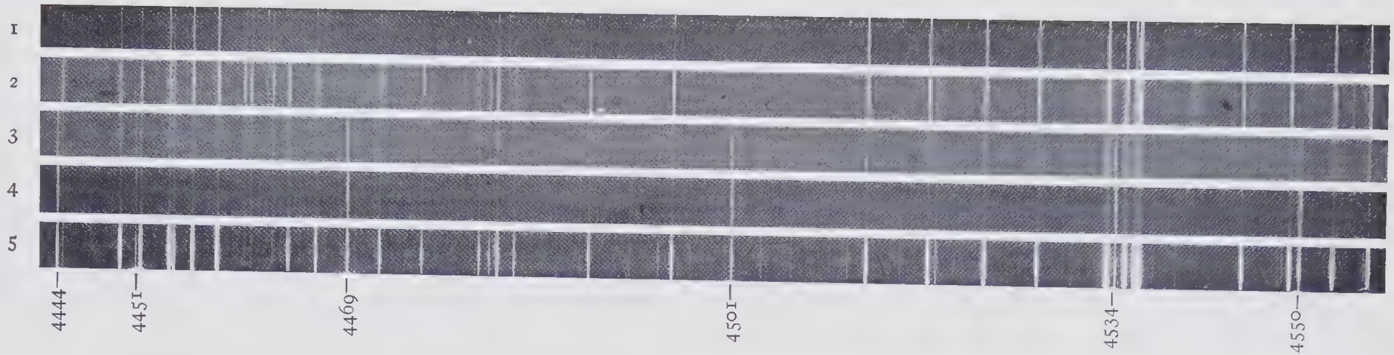
In the previous experiments very high temperatures were occasionally employed, but with only moderate dispersion, so that the continuous spectrum given by such a temperature was strong enough to conceal faint lines. An increase of scale was required, combined with brightness of the spectrum. Fortunately, a new plane grating was available, ruled by Anderson on the Rowland machine, which gave very bright spectra in the first and second orders in spite of its small area (6.3×7.2 cm). The second order of this grating was used in the Littrow spectrograph of 30 ft. (9.1 m) focal length, the scale being approximately 0.9 Å. per mm. The photographs were made on Cramer "Crown" plates for the region from λ 4220 to λ 4600, in which range titanium has about forty enhanced lines of varying intensities, but all showing a behavior in arc and spark quite typical of this class.

The tube resistance furnace was used with its parts arranged as described in previous papers, but without any jacketing material around the tube. The chamber was pumped out to a low pressure. The tubes of Acheson graphite first employed were 12.5 mm inside diameter, 18.3 mm outside diameter, and 30.5 cm long, the heated portion being 20.3 cm long. A potential of 30 volts on these tubes gave 1600 amperes, falling to about 1500. Pyrometer readings for several trials gave above 2600° C, when the instrument was sighted at the interior of the tube. This value is probably low, being measured for an open tube. Under such conditions, all of the stronger enhanced lines appeared very distinctly for exposures lasting 3 minutes. A 2-minute photograph, showing less continuous ground, is reproduced as No. 2 of Plate XXI. The enhanced lines are plainly visible in the negative, but can hardly be expected to show in the reproduction. No. 1 in this plate is the spectrum for about 2400° and shows no enhanced lines.

We thus have the result that the temperatures attainable in the furnace, when operated in the regular way, will give all classes of titanium lines, and so far as the examination of the visible spectrum has proceeded, it appears that all lines of titanium appearing distinctly in the arc can be obtained in the furnace.

The next step was an attempt to obtain still higher temperature by the use of thinner tubes. Tubes with slightly thicker walls

PLATE XXI



Titanium Spectra Given by Electric Furnace and Arc, Showing Development of Enhanced Lines when Tube Burns Through

1. Regular furnace spectrum for about 2400° C
2. Regular furnace spectrum for about 2600° C
3. Spectrum when slit was covered just after tube burned through
4. Spectrum given chiefly by conditions following break of tube
5. Spectrum of carbon arc containing titanium, taken on same plate as 4. The stronger enhanced lines are marked

than those previously used were turned down so as to give a wall about 2 mm thick for 5 cm at the middle of the tube, the powdered titanium carbide being placed in the middle of the thin portion. As surprising effects were soon obtained with these tubes, the experiments will be described in some detail.

A preliminary heating for 1 minute at about 1000 amperes drove off the more volatile substances, but did not melt the titanium. The tube would stand 1400 amperes at 25 volts for several minutes, giving a rich titanium spectrum with the enhanced lines visible. When 30 volts were placed on the tube, the current went above 1600 amperes (the limit of the ammeter scale), remained there a few seconds and began to drop, while the appearance of the image of the tube's interior projected on the slit showed that a violent vaporization of carbon was taking place. When below 1500 amperes the current fell rapidly, showing that the tube was burning through, with the formation of an arc. This arc often held for 5 seconds or more with the ammeter usually registering about 800 amperes, before the ends of the tube were burned so far apart that the arc broke. During this time a voltmeter connected across the furnace terminals remained close to 30 volts, though increasing 2 or 3 volts at the beginning of the arcing stage. With a gradual burning around the circumference of the tube before the formation of the arc, it is doubtful if a high momentary voltage occurred such as would result from a sudden complete break. The voltmeter would not have recorded this and tests have shown that the spectra obtained were not materially influenced thereby.

When the furnace was opened after cooling, the tube was found burned apart near the middle of the thin portion, a space of 3 to 4 mm separating the edges all around the circumference. (Contraction of the parts during cooling may have altered the original interval.) Each section of the broken tube thinned down gradually at each side of the break, beginning about 1 cm from the sharp edge, showing how the carbon had vaporized with decreasing violence at each side of the weak point where the break occurred. An interesting feature was that this vaporization took place almost entirely within the tube, the outside diameter remaining the same up to the break. This was doubtless due to the strong radiation from the exterior of the tube, no jacket being used.

By making a large number of runs of the furnace with tubes of the same kind, it has been possible to photograph the spectrum given at various stages of the run which, from the time of turning on the 30-volt current to the final breaking of the arc, never lasted more than 30 seconds. Three plates were made for the conditions prior to the breaking of the tube, when it was wearing thin with strong vaporization of the carbon. The slit was covered as nearly as possible just before the instant of break. These plates were underexposed, but the enhanced lines, though faint, were relatively strong in reference to the arc lines as compared to photographs taken under the regular furnace conditions with a long tube of uniform thickness. This evidence indicates a slight relative strengthening of the enhanced lines with rising temperature while furnace conditions may be considered still to exist.

A photograph for which the slit was covered just after the tube burned through is shown as No. 3 of Plate XXI. This registers for the most part the conditions preceding the break, but in the short interval in which the plate was exposed during the burning of the tube the enhanced lines appeared so strongly that the integrated effect gives them about the same intensity relatively to the arc lines that they usually have in the carbon arc containing titanium. Number 4 of Plate XXI represents a stage more favorable to the enhanced lines. The tube broke sooner than usual and the plate was exposed after the break longer than in the case of No. 3. The enhanced lines are seen to predominate strongly in the spectrum. The relative intensities resemble those of the condensed spark, but the arc lines show the peculiar softness characteristic of furnace lines. Spectrum No. 5 is that given by the carbon arc containing titanium, from which the usual strength of the enhanced lines in the arc may be seen.

It is evident from the way the enhanced lines stand out in No. 4 of Plate XXI that conditions during and after the burning through of the tube are especially favorable for the production of these lines. A consideration of what transpires during this part of the experiment shows that we have here a source different in many respects from the furnace, arc, or spark as regularly operated, and perhaps approaching nearer to the conditions of radiation in solar and stellar atmospheres than is done in any of our laboratory sources. An important point is the high concentration of electrical energy over a very short stretch of the tube. Just before the break the transformer supplies from 40 to 50 kilowatts, a very large part of which must be used over the 5 cm of thin tube, the rest of the circuit being made up of low-resistance connections and the relatively thick tube at each side of the turned-down portion. When the tube has burned very thin at the weakest portion, the rupture must be in the nature of an explosion, in which probably the highest temperature is generated that can be obtained from carbon at the existing pressure. When the tube has burned through around its circumference, the vapor inside whose light falls upon the slit may be considered as surrounded by a wall of arc which must consume nearly all of the 24 kilowatts which the transformer usually supplied for a period of from 5 to 15 seconds. When we consider that the power ordinarily used for an arc in the laboratory is less than 500 watts, the energy consumed in the two sources is seen to be of quite a different order.

While the conditions following the break of the tube are widely different from the regular furnace conditions, the low potential employed furnishes an important difference from the arc or spark. As has been noted, the voltage across the terminals outside the furnace appeared not to rise above 33 volts. Granting the possibility of a high momentary potential which the voltmeter would not follow, experiments have shown definitely that the conditions favorable to the enhanced lines extend through the arcing period and are not limited to the instant of explosion. The most decisive test on this point was made by taking two successive photographs, the exposure for one being made as the tube burned apart, that for the other beginning about 10 seconds later. The second photograph showed all of the enhanced lines in that region, and very little besides.

The foregoing experiments had been made with an image of the interior of the tube about 2 cm in diameter projected on the spectrograph head, the light which passed through the slit (4 mm long) being taken from the central part of the image. It now occurred to me that there might be a distinct difference between the spectra given by the vapor at the center and by that near the wall where the arc was in action. As the spectrograph shows almost no astigmatism, it was a simple matter to test this. The length of slit used was increased so as to pass across the diameter of the image from wall to wall. When a tube was used at a temperature which did not burn it through, there was no perceptible difference in strength or appearance of the lines from center to wall, so that in the regular operation of the furnace the long slit offers no advantage.

For the conditions when the tube was burned through, however, a difference of the most striking nature appeared. The non-enhanced lines were much weaker in the center of the tube than near the wall, *while the titanium enhanced lines showed almost no change in intensity across the diameter of the tube.* In other words, the enhanced lines were very strong in the middle of the tube relatively to the lines characteristic of the arc. This phenomenon was photographed on six plates with no variation in the general features.[1] The spectra in Plate XXII were made with the long slit as described, and are reproduced almost full scale. Each spectrum is in two sections. No. 1 is a true furnace spectrum taken with a turned-down tube but with only 25 volts, which did not burn it through in the minute required for the photograph. Nos. 2 and 3 were made by exposing at the moment of break with 30 volts on the tube. The enhanced lines are marked in No. 2. Spectrum No. 3 has less general intensity and the enhanced lines stand out in the middle of the strip more distinctly than in No. 2. The uniformity of intensity across the diameter of the tube makes the selection of the enhanced lines a matter of the greatest ease, and is striking evidence of their dependence on a different physical condition of the vapor than that favorable to the non-enhanced lines and to the carbon flutings,

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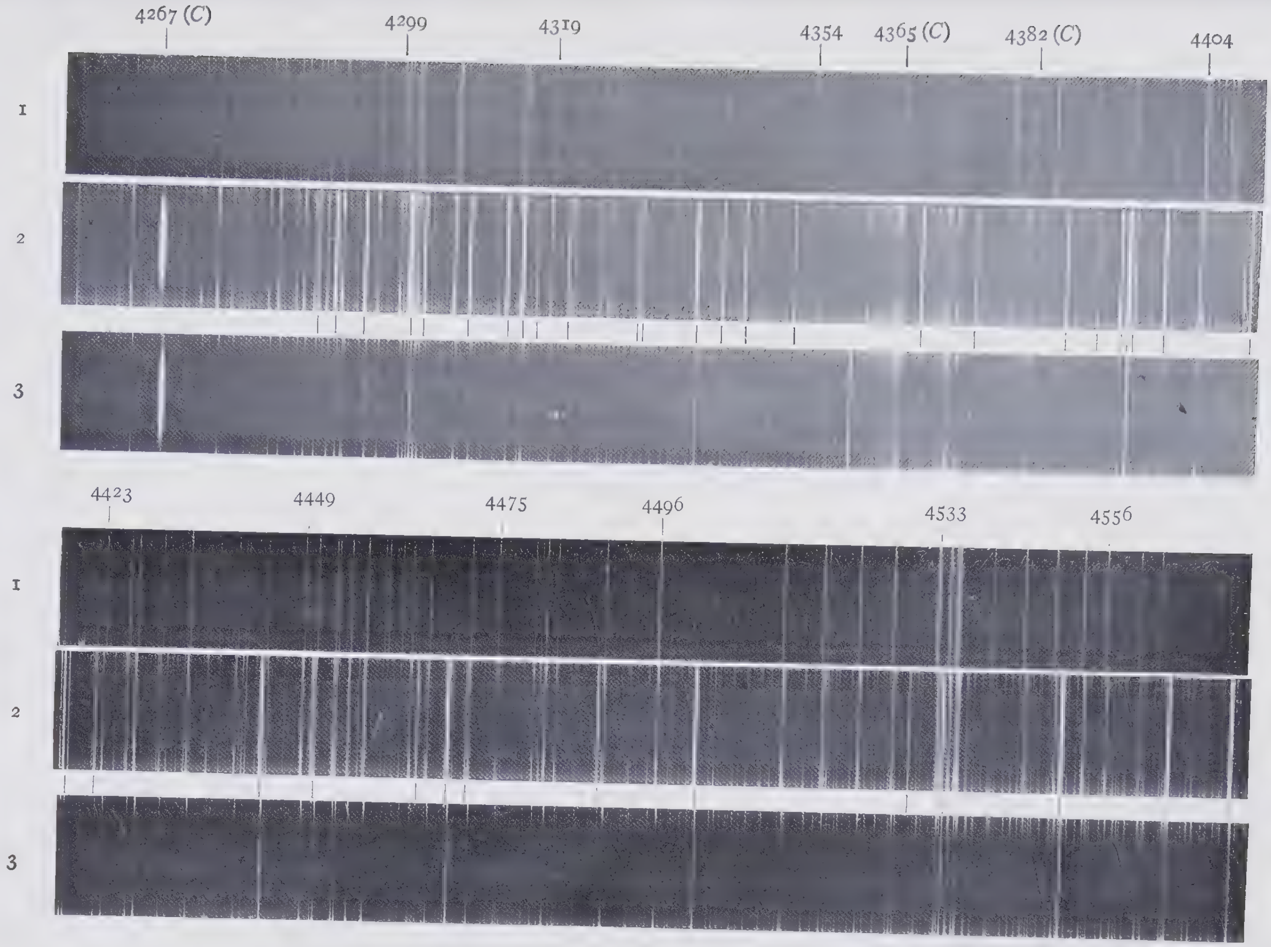
[1] Note added January 1913:

Supplementary photographs have been taken extending from λ 3900 to λ 5227, in which all of the titanium enhanced lines in this range have been obtained in the broken-tube spectrum. Their intensities relative to the arc lines were found to be fully in accord with those of the lines discussed in this paper.



SPECTRA OF THE ELECTRIC FURNACE PHOTOGRAPHED WITH LONG SLIT, SHOWING HIGH RELATIVE INTENSITY OF ENHANCED LINES IN CENTER OF TUBE WHEN TUBE BURNS THROUGH

Scale: 1 mm = 1 Å

1. Regular furnace spectrum with unbroken tube

2 and 3. Spectrum given after tube burns through. Titanium enhanced lines are marked on margin of 2

of which the band with heads at λλ 4382, 4371, and 4365 comes out strongly. At λ 4267 appears the spark line of carbon, strong in the center and scarcely visible at the wall of the tube, its behavior being just opposite to that of the carbon bands. This line will be discussed farther on.

The enhanced lines would thus seem to show a distinct lack of dependence upon either temperature difference or potential fall. A temperature difference as we pass from the arcing wall of the tube toward the center is to be expected, and this is borne out by the diminution in intensity of the non-enhanced lines. The carbon flutings also, whose intensity in the regular furnace closely follows the temperature, are much weaker in the center of the tube. Likewise, such potential fall as there is in this low-voltage arc must be much greater close to the wall than at a point in the center of the tube 6 mm distant from the arcing point. If a decided difference in vapor density prevails between center and wall of the tube, the enhanced lines might be less affected by this than the arc lines. It is difficult to say how great a difference of this sort there may be, but the width of the arc lines, which is governed largely by the vapor density, seems to decrease less rapidly toward the center of the tube than does their brightness, which is controlled, for this class of lines, chiefly by the temperature.

The spark line of carbon, λ 4267, shown on Plate XXII, appeared on all plates taken with the burned-through tube, being strong and unsymmetrically reversed in the center of the tube, and decreasing in strength toward the wall, until it was almost invisible at the edge of the image representing the point nearest to the hot carbon. As has been noted, the vaporization of the carbon was very violent under the conditions of this experiment, but the line does not appear in the furnace when the tube does not break nor in the carbon arc burning with continuous current. Crew and Spence[1] obtained it in an arc in which one terminal was a rotating disc of graphite. They describe its behavior as follows:

> A very curious thing happens with this rotating graphite arc, viz., the appearance of the well-known carbon spark line at λ 4267, a *Hauptlinie* of Eder and Valenta. Few lines are so sensitive to rapid changes in E.M.F.

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[1] *Astrophysical Journal*, **22**, 199, 1905.

This line is strong in the spark between amorphous carbon poles, *provided they are cold;* if, however, the carbon tips have been heated, the line disappears even from a powerful transformer spark. On the other hand, this line which does not appear in the ordinary carbon arc comes out strong in the rotating graphite arc, where the natural quickness of break which characterizes the graphite arc is accentuated by the motion of the electrode. In other words, this line disappears with great readiness from its natural source (the carbon spark) and appears, on slight provocation, in a source where it might be least expected, the graphite arc. Such capricious behavior might lead one to hesitate in assigning this line to carbon; but its presence in pure Acheson graphite leaves little room for doubt as to its identity.

It is characteristic of enhanced lines in general that they weaken in the spark when the electrodes become hot; also, that such lines in many cases are given by the rotating arc used by Crew,[1] especially when operated in an atmosphere of hydrogen. The decrease of potential gradient in the spark with hot electrodes and the increase due to the sudden break in the rotating arc have been given as the most plausible explanation of this behavior of the enhanced lines. An extended investigation may prove that this conduct of the carbon line λ 4267 is typical of those enhanced lines which do not appear at all in the arc when burning continuously, such lines being a step more difficult of production than the titanium enhanced lines. When we have a source of great energy like the burned tube which is able to produce lines of all classes, the present evidence indicates that the arc lines, the titanium enhanced lines, and such lines as λ 4267 form a sequence for which a high potential gradient is not necessary and the region of highest temperature becomes increasingly unfavorable for the successive classes. The proximity of hot carbon appears as destructive to the carbon spark line in the furnace as in the spark while as we recede from the walls the vapor rapidly becomes better able to give this line.

Another highly interesting phenomenon appears in the spectrum when the tube burns through. The ends of the long lines, given by the vapor close to the arcing walls, show nearly uniform brightness across their width, while as we approach the middle, the red side of the line becomes constantly stronger. If the line is reversed, the dissymmetry of the two sides is very marked; if unreversed,

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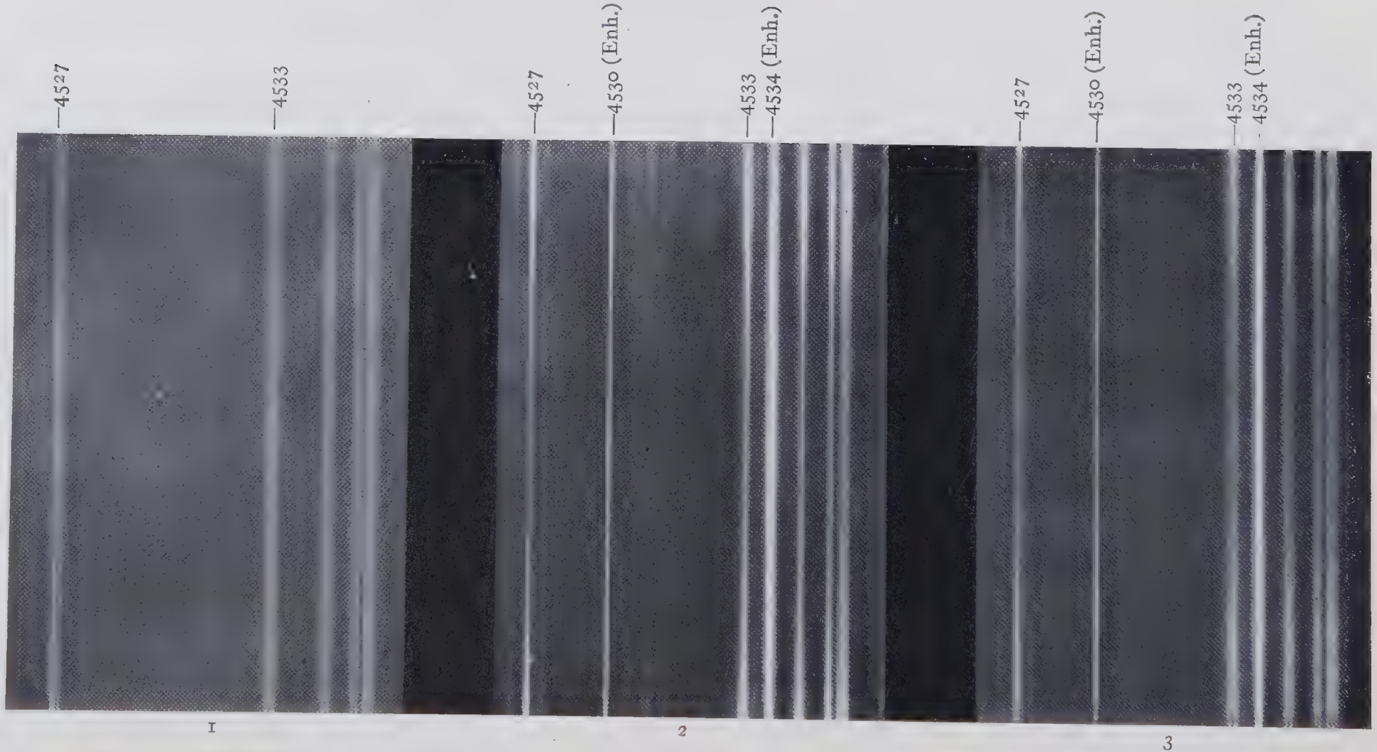
[1] *Astrophysical Journal*, **12**, 167, 1900.

PLATE XXIII



Spectra Taken with Long Slit before and after the Break of Tube in Electric Furnace, Showing Dissymmetry of Lines after Break, together with Appearance of Enhanced Lines

1. Regular furnace spectrum with unbroken tube
2. Spectrum when plate was exposed at moment of break
3. Spectrum combining effects of 1 and 2, exposure covering period before and after break of tube

chiefly the red side remains at the middle. This difference does not show for the titanium enhanced lines, though these lines being narrow and "hard" could not be expected to show it so distinctly if it is present. The spark line of carbon is very unsymmetrically reversed (see Plate XXII), the red side being almost twice as strong as the violet.

The effect, as compared to the regular appearance of the furnace line, may be seen in Plate XXIII. Three spectra are shown, taken with the same sort of tubes and the same optical arrangements, the conditions for the third being a combination of those for the first two. No. 1 is a regular furnace spectrum exposed 1 minute. The lines show little difference in intensity from end to end and are symmetrical in structure, whether reversed or not. Traces of the enhanced lines are barely visible in the negative. No. 2 is the broken-tube spectrum taken in 15 seconds, the plate being exposed at the moment of break. The large scale shows to advantage the variable intensity of the arc lines from end to end as compared with the unchanged condition of the enhanced lines, but it is given chiefly to illustrate the difference in structure at center and ends of the arc lines. The reversed lines show almost complete symmetry when given by the vapor near the wall of the tube, while in the middle of the tube little remains of the violet side of the line. The unreversed line $\lambda 4527$ has the same structure narrowed down. No. 3 was made by an exposure of about 1 minute before the break, followed by 12 seconds while the tube was burning through and arcing. The superposition of the two states is seen in the presence of strong enhanced lines, while the arc lines are nearly in the state of No. 1, but show a weakness and dissymmetry in the middle caused by the short period corresponding to No. 2.

These photographs seem to offer unmistakable evidence of a difference in condition between center and wall of the tube which affects the structure of the line. Whether it is a real shift of the maximum or an unsymmetrical widening cannot now be decided. It is probably the latter, but in any case it is a disturbance which would greatly affect wave-length measurements and must be recognized as a condition likely to occur in any source in which the vapor approaches a state such as we have here. As would be expected, different photographs do not show this effect in the same degree. The general condition is always the same, but the violence of the rupture of the tube and resulting arc will not be alike in two experiments. A variability of the excitation during the time of an exposure is evident from the poor definition of the lines given by the broken tube, indicating the integration of a changing state; while the regular furnace lines, if the temperature is kept constant, are excellent for measurement. This difference in the quality of the lines is plainly seen in Nos. 1 and 2 of Plate XXIII.

The connection of this effect with another spectroscopic phenomenon is of special interest. It is well known that the condensed spark gives lines whose wave-lengths in many cases measure greater than in the arc.[1] Whether this is a real displacement or not, measurements are affected to such an extent that lines given by a strongly condensed spark are useless for accurate standards. The conditions in the middle of the furnace tube, when broken, give lines of such relative intensities as are obtained in the laboratory only with very powerful sparks, and we have the same apparent displacement toward the red as in the spark, when referred to the end of the line which is produced by vapor apparently more nearly in the state of the arc. This difference in the case of the furnace spectrum can scarcely be ascribed to pressure, a hypothesis for the spark which has been carried to the extent of estimating the pressure of the spark from known values for pressure displacements.

These preliminary observations appear very promising in the way of furnishing supplementary data as to the conditions for producing the enhanced lines, our knowledge of which has advanced slowly owing to the more or less conflicting evidence given by the arc and spark phenomena. Among the astrophysical applications, which can be made when observations for a number of elements are available, one of the most important will probably be to the spectrum of the chromosphere. The presence of enhanced lines in the upper regions of the sun's atmosphere agrees with the furnace results in that these lines may appear in regions where the highest temperatures are not to be expected.

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[1] See, among others, N. A. Kent, *Astrophysical Journal*, **22**, 182, 1905.

SUMMARY

The leading features brought out in this study may be summarized as follows:

1. The enhanced lines of titanium appear in the regular furnace spectrum for temperatures probably somewhat higher than 2600° C; but are very faint compared to the arc lines.

2. At still higher temperatures, while furnace conditions still exist, there are indications of a slight increase in the relative strength of the enhanced lines.

3. When the furnace tube burns through with the formation of a low-voltage arc, the consumption of electrical energy at the point being very large, the enhanced lines of titanium and the spark line λ 4267 of carbon appear with an intensity usually attainable only in powerful sparks.

4. By photographing with the slit across the image of the tube's interior. the relative strength of the enhanced lines is seen to be much greater in the center of the tube than near the wall, this effect being very pronounced in the case of the carbon spark line.

5. The vapor in the center of the broken tube shows a tendency to give a line farther to the red than that near the wall, this being shown in the increasing dissymmetry of the lines from the end toward the middle. The effect is in harmony with the action of the condensed spark.

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THE VARIATION WITH TEMPERATURE OF THE ELECTRIC FURNACE SPECTRUM OF IRON

By ARTHUR S. KING

It is well known that the spectrum of a given element is usually subject to large variations depending on the physical conditions of the radiating source. The differences between flame, arc, and spark spectra have been studied, with a considerable divergence of opinion among investigators as to how largely these differences may be ascribed to temperature rather than to the electrical and chemical conditions which are manifestly present in different degrees in the several sources. Between the flame and the arc, overlapping in temperature some of the hotter flames, stands the tube resistance furnace, with which the investigation now to be described has been carried out. By the use of this apparatus, any desired steps of temperature may be obtained and measured, up to a point where the vaporization of the carbon tube becomes excessive. The resulting spectra show a progressive change in the relative intensities of lines with increase of temperature. It is the purpose of this paper to give the intensities of iron lines as produced by the furnace at low, medium, and high temperature, and a comparison in some detail with the arc spectrum, together with some mention of the spectra from other sources. The material available shows not only the approximate temperature at which a given line appears in the iron spectrum, but also the rate at which the line strengthens with increasing furnace temperature and with the change from furnace to arc. The classification based on these results will, it is hoped, aid in showing to what extent an observed variation in the spectrum of a given source is to be ascribed to temperature differences.

APPARATUS AND METHODS

1. *The electric furnace.*—A general description of the tube resistance furnace used in the Pasadena laboratory was given in

the first publication concerning it.[1] The furnace consists essentially of a tube of Acheson graphite, each end of which is clamped in a contact block which connects it with one of two water-cooled copper pipes leading in the current. The whole is inclosed in a heavy steel cylinder cooled by water-jackets, the electrode tubes passing through one head of the cylinder. Windows in each end allow light from the furnace tube to pass to the spectrograph and also permit of pyrometer measurements.

The contact blocks, instead of being entirely of graphite, as in the original design of the furnace, have been improved by making them of massive blocks of bronze 5 cm thick, sawed from top to bottom, and fitting around the upper or lower electrode tube as the case may be. In the center of each contact block is a cylindrical cavity into which fits a disk of graphite 5 cm in thickness and 7.6 cm in diameter, sawed across the vertical diameter and bored in the center to receive the end of the graphite tube, which is usually about 19 mm outside diameter, 12.5 mm inside diameter, and 30.5 cm long. These contact blocks give little variation in contact resistance, the surfaces being smooth and of large area. The two halves are fastened together by four horizontal bolts and when these bolts are moderately tight the smooth contact surfaces between bronze and graphite allow enough slipping to prevent breaking of the tube through relative expansion of the connections.

In the earlier experiments, the furnace tube was inclosed by a split graphite tube which was surrounded by loose carborundum as heat insulation. In the work done by the writer with the furnace filled with air or carbon dioxide at high pressure[2] such a jacket is almost indispensable on account of the rapid oxidation of the tube, if it is exposed directly to the compressed gas, and the strong convection of heat to the steel walls of the chamber. In comparing the spectra at various furnace temperatures, however, the chamber is regularly pumped out to a pressure of less than

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

[2] *Contributions from the Mount Wilson Solar Observatory*, Nos. 53 and 60; *Astrophysical Journal*, **34**, 37, 1911, and **35**, 183, 1912.

2 cm of mercury, and, when this is done, a much greater constancy of temperature is obtained by using no heat jacket. The tube then quickly reaches an equilibrium of temperature, which varies little during the time usually required for a photograph. With the carborundum jacket, on the other hand, the tube temperature increases steadily for some time, on account of the slow heating of the jacket, so that either a reduction of the impressed voltage or occasional breaking of the current for a few seconds is required to prevent too large a temperature variation during the run. Dispensing with the jacket naturally requires a larger current to produce the same temperature of the tube, but if sufficient power is available, the greater constancy of the temperature is a decided advantage.

The 50 K.W. transformer used for the furnace gives a range by 5-volt steps from 5 to 30 volts. For the temperatures employed in these experiments, potentials from 15 to 30 volts were generally used, the currents ranging from 800 to 1600 amperes.

2. *Measurement of temperature.*—Observations with a Wanner pyrometer were taken regularly during the operation of the furnace, the interior of the furnace tube being viewed through the window opposite to that directed toward the spectrograph. This method should give reliable values for the relative temperatures at which spectra were successively obtained, which was the chief object in the present work. The reading necessarily gives a mean value of the temperature from end to end of the tube, assuming that the departure from black-body conditions is not great, since the line of view can be inclined only slightly to the tube's axis, and thus the temperature of any particular part of the tube is uncertain. Attempts have been made to measure the temperature at the center of the tube by placing a graphite plug midway in its length. Readings of the pyrometer when directed at this plug have given temperatures 100° to 150° higher than the mean temperature when viewed without the plug. The temperature of the plug does not correctly give that of the adjacent wall of the tube, but is probably close to it by reason of the high heat conductivity of graphite. It is also an open question how nearly the temperature of metallic vapor inside the tube agrees

with the temperature of the tube itself. These points, however, do not invalidate the relative measures required in this investigation.

3. *Photography of the spectrum.*—Large-scale photographs of furnace spectra have been used as far as possible, having the obvious advantages of avoiding blends and showing more clearly the character and structure of the lines. The vertical Littrow spectrograph described in previous publications[1] was employed, the arrangement most used being with an objective of 30 feet (9.1 m) focus and a Michelson plane grating of 7.2×19 cm ruled surface, of which area only a part about 5×15 cm could be used for the best definition. The dispersion for the first order varied from 1.95 Å per mm in the blue to 2.06 Å per mm in the red. The range from λ 3880 to λ 6600 was covered on this scale. A large part of the spectrum, including the portions where lines are most numerous and variable, was later photographed in the second order with a dispersion close to 0.95 Å per mm. The plates were 9.2×43.2 cm in size, the emulsions most used being the Seed "Gilt Edge 27," the Cramer "Inst. Isochromatic," and the Seed "27" bathed with the Wallace three-dye solution of pinacyanol, pinaverdol, and homocol.[2] Cramer "Crown" plates were also used for some photographs in the blue region.

The spectrum beyond λ 6600 and to the violet of λ 3880 has been photographed with a concave grating spectrograph recently constructed, which gives very bright spectra with excellent definition. Many photographs of the visible region were also taken with this and used chiefly to check the large-scale plates. The grating in this instrument is of 1-meter radius and 5.1×8 cm ruled surface, and was made by J. A. Anderson on the Rowland dividing engine. It is mounted, with slit and camera-box, on a rigid steel frame, inclosed in a light-tight case. As adjusted, the spectral region covered is approximately from λ 2000 to λ 8000 in the first order, a strip of film 38 cm long being used in a metal holder. In the work thus far, the regular Eastman kodak film has been used. It is sensitive for strong lines to about λ 5600, with a gradual decrease from the blue to the yellow; but the sensitiveness to the red of λ 5000 is much increased by the three-dye bath, which the films take very satisfactorily. The sharp definition permits the films to be examined under a high magnification, so that a preliminary survey of the ultra-violet in the second order (dispersion 1 mm = 8.5 Å) was made to good advantage, the first order being used in the extreme ultra-violet on account of its strength. This small spectrograph has been mounted at the end of the furnace opposite to that which is directed at the large Littrow instrument, and simultaneous photographs were frequently taken, giving a long range of spectrum for the same conditions under which a selected region was photographed by the large-scale spectrograph.

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[1] Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 27; *Astrophysical Journal*, **28**, 244, 1908; King, *Carnegie Institution of Washington Publication*, No. 153, 13, 1912.

[2] *Astrophysical Journal*, **26**, 299, 1907.

4. *Operation of the furnace.*—The furnace having been placed in position, with a quantity of iron filings in the tube, and the current turned on, an image of the interior of the tube was focused on the slit of the spectrograph employed, the focusing lens of glass or quartz being selected of such focal length as to give an image of convenient size on the slit, and at the same time fully to illuminate the grating. The fixed character of all parts of the furnace prevents any change in the illumination of the grating such as often occurs with other sources.

Furnace spectra for two and sometimes three different temperatures were usually taken on the same plate, the exposures being timed so as to give a number of prominent lines about the same intensity in each photograph. Several arc spectra were added with varying exposure times by reflecting the light from an iron arc through the same lens as was used for the furnace exposures. This gave a means of easy identification of the furnace lines together with a number of arc spectra, from which the one whose average intensity was best suited for comparison with the furnace spectra could be selected. Since the first-order spectrum of the 30-ft. (9.1 m) spectrograph gave almost 800 Å on a single plate, it will be seen that a plate properly exposed furnished a large amount of material in which photographic differences, especially in the matter of development, did not enter. While special weight was given to a few photographs of exceptional quality, these have been fully checked by other good plates taken with both the large and the small spectrographs, the former including a number of second-order spectra for the detection of possible blends.

Three approximate temperatures were chosen, which will be referred to as low, medium, and high. Pyrometer readings for these, taken in the manner already described, gave values of 1800° to 1900° C. for the low temperature, 2100° to 2300° C. for the medium, and 2500° to 2700° C. for the high temperature. The intensities of lines were estimated on at least three good plates, and frequently more, for each range of temperature, the results being consistent enough to enable one to place pretty definitely the position of a plate on the temperature scale by the relative intensities of certain lines especially sensitive to temperature change.

THE GENERAL PHENOMENA OF VARIATION OF SPECTRA WITH FURNACE TEMPERATURE

The arc spectrum under certain conditions, in general those given by the central region of the arc, not close to either pole, is usually taken as the standard for such substances as can be volatilized to advantage in the arc, by reason of the richness in lines and the approximate constancy of relative intensities in the spectrum thus produced. As compared with the arc spectrum of iron, the furnace spectrum shows marked differences at all stages of temperature. At the lowest temperature at which the vapor radiates, a group of lines appears which includes not only some of the strongest arc lines but also other lines which are only moderately strong and others which are quite faint in the arc. Many very strong arc lines are entirely absent. As the temperature rises, other lines appear, but by no means in the order to be expected from their arc intensities; and by taking a range of temperature such as was used in these experiments it is seen that *the lines grow in intensity with temperature at very different rates.* Part of the lines which appeared at the lowest temperature increase in intensity very slowly, some of them, in reference to the majority of the lines, actually seeming to weaken slightly at the higher temperatures. Other lines about hold their own, while many of the representative arc lines increase very rapidly in intensity. At the highest furnace temperatures, the furnace spectrum compares closely in richness with that of the arc; in fact, experiments thus far have indicated that it is chiefly a matter of long exposure to bring out practically all of the arc lines in the furnace at high temperature. The differences in relative intensities of lines, however, are still large, with two extreme types. One class includes lines very strong in the arc which are produced faintly only with great difficulty in the furnace. Lines of the other class are strong at all furnace temperatures, and in the arc are of moderate strength, sometimes very weak. Between these extremes there is a large variety in the behavior of the furnace lines which will be made the basis of the classification to be given.

THE STRUCTURE OF FURNACE LINES

In a previous paper by the writer on the pressure-shift of furnace lines,[1] attention was called to the width of the lines in proportion to their density as possibly being connected with their sensitiveness to pressure displacement. This structure has been studied farther in the spectra taken with the furnace *in vacuo* at different temperatures.

The vapor distribution in the furnace differs materially from that in the arc. We have in the furnace tube a very gradual decrease in temperature and vapor density from the middle toward either end. At the lowest temperature for which a spectrum can be obtained, only the vapor in the central portion is hot enough to radiate. The lines are then comparatively narrow, "hard," and can be given any desired blackness in the negative by long exposure. A higher temperature results in vapor nearer the ends of the tube being made hot enough to radiate, and therefore absorb, the central vapor at the same time giving a wider line. The effect of this gradual increase in the absorptive power of the vapor as it nears the end of the tube is to soften the middle of the spectrum line and give all variations as the temperature of the tube increases, from a hard, narrow line to complete self-reversal, provided that the rarer vapor near the ends of the tube ever becomes hot enough to radiate (and absorb) the wave-length in question. A short range of spectrum photographed at high temperature will often illustrate the steps in this process by different lines. Those lines which the hottest vapor at the center of the tube is barely able to give are narrow. Other lines not requiring so high a temperature show the gradual widening with softening of the center, through the diffuse stage which precedes reversal, and then clear reversals for such lines as are given by the vapor close to the end. While these conditions for reversal are necessary, they are not always sufficient, since the ease of reversal of iron lines increases toward the violet end of the spectrum and may vary for different lines in other respects which the present investigation has not shown.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 60; *Astrophysical Journal*, **35**, 183, 1912.

INTENSITY SCALE

It would be highly desirable to place the grading of line intensities on a strict photometric basis; but all who have attempted this have met the fundamental difficulty that the increase of width with density as a line strengthens is very different for different lines. A scale of blackness alone (for lines in the negative) would be highly misleading. A scale made by successive photographs of an actual spectrum line whose intensity could be closely controlled and made to increase at a known rate could be used only for a class of lines showing the same behavior as regards the increase of width with density. Even this would involve large errors when the photographic scale was compared with spectrum plates differing in contrast and amount of development, and not always normally exposed. Different scales for sharp and diffuse lines would be quite necessary, and there is a wide variation in each of these classes. Further, the comparison of narrow, dense lines with widely reversed lines would seem to be beyond the reach of such a method.

These difficulties, which are general for emission spectra, are increased when furnace lines for different temperatures are compared. The rapid widening and softening of a line with increased temperature, mentioned in the preceding section, makes it harder to compare with the appearance of the same line at low temperature, where it is narrow and its density is given by long exposure. When, however, the spectrum for a given temperature is considered by itself, it is found quite possible to grade the line intensities in a consistent manner when all features of a given line are considered.

Proceeding in this way in the present work, a line distinctly outlined on the plate has been graded "1," a fainter appearance being indicated by "trace." If, as was usually the case, none of the lines were exposed to reach full blackness in the negative, a grading of intensities for the various lines could be made which would be confirmed with small variations on a second examination of the plate by the same person, and with differences only slightly greater by another observer. The extension of the scale to include reversed lines was not difficult, since the portion of spectrum being studied usually offered lines in various stages preliminary to reversal whose position in the scale between sharp lines and those fully reversed was fairly distinct. The steady character of the furnace radiation and the dependence of a line's intensity on the portion of the tube where the vapor is in a condition to produce the line permit a grading of this kind to be more consistent than is often the case with the arc or spark. The lines for a different furnace temperature are graded in the same way. In the final tabulation, if a line is graded 10 for two temperatures, this does not mean that the line is exactly alike as regards width and density in the two cases, but that it bears the given relation to the lines in its own spectrum for each temperature.

The writer is well aware that personal and photographic differences enter to an undesirable degree in this method of assigning intensities, but where the aim is to tell whether at a certain stage of temperature a line appears on a normally exposed plate and to give its approximate intensity compared with other lines at the same temperature, I believe the method pursued fulfils the requirements better than photometric measures which would require constant modification by a consideration of the general appearance of the spectrum line concerned.

THE TEMPERATURE CLASSIFICATION OF IRON LINES

In pursuance of the object of indicating the relative response to temperature of different lines, both as to the stage of initial appearance and the rate of growth with increase of temperature, six classes have been formed. A reference class is required, which should be made up of a number of lines which are strong at all temperatures and show about the same rate of change. This is the group to be designated as Class I B. They are plentiful throughout the spectrum, except in the orange and red, and the photographs have been made so as to give these lines nearly the same intensity for different temperatures.

Class I A has the distinguishing characteristic of strength at all furnace temperatures after the vapor begins to radiate, and notable weakness in the arc. As compared to the reference group I B, some I A lines show a slight weakening as the temperature increases, but they remain among the stronger furnace lines at the highest temperature. In the arc, however, they are among the weaker lines, sometimes being barely visible in a normally-exposed arc spectrum. Care must be taken to distinguish these from impurity lines which show a similar behavior, the strongest lines of a foreign substance often being given with greater intensity in the furnace than in the arc between iron terminals. To make the identification of the lines of Class I A as certain as possible, all of them have been photographed in the second-order spectrum with a scale of about 0.95 Å per mm, an arc spectrum being taken on the same plate with the ends of the furnace and arc lines overlapping. The I A lines were found to coincide exactly in every case with faint arc lines which are regularly ascribed to iron in the wave-length tables. Possibly a few of these lines appearing in the iron arc may be shown later to belong to foreign substances, a point which has not been thoroughly investigated in this laboratory, but their regular behavior in the arc and spark is that of weak iron lines, so that the phenomena offered by this important class may be regarded as in all probability real.

Class I B embraces the well-known group of "flame" lines which are given readily in the hotter flames and are relatively strong in the outer envelopes of the iron arc. In the furnace they are strong at all temperatures, being taken as the reference group in this classification. In the arc they are usually of moderate strength, although those in the green-yellow are among the strongest arc lines. There is usually a clear distinction in the arc between these and the lines of Class I A, for which the arc conditions appear to be distinctly unfavorable.

Class II includes a large number of the stronger arc lines. In the furnace they are distinct, often strong, at the lowest temperature, but as the temperature rises, these lines strengthen much faster than the lines of Class I, and are usually found to have gone up rapidly in the interval between the highest furnace temperature and that of the arc.

Class III lines are absent or faint at the lowest temperature, appear distinctly at medium temperature, show a rapid growth at high temperature, and are strong in the arc. Their rate of growth is similar to the lines of Class II, but they require a higher initial temperature for their production.

Class IV lines appear only at the highest furnace temperature (perhaps as a trace at medium), but show a fair strength. Their arc intensity is usually relatively much greater than in the furnace.

Class V includes lines which are absent or very faint in the furnace, their strength in the arc varying greatly. Experiment has shown that it is possible to bring out many if not all lines of this class by prolonged furnace exposure at high temperature, but the difference between their arc and furnace intensities is greater than for Class IV. In the blue and violet, where impurity lines from several rich spectra are somewhat troublesome, lines entered as "trace" or "1" at high temperature may occasionally belong to foreign substances, as their weakness made them difficult to obtain on the largest-scale plates and hard to measure closely when they did appear. If any of these are not due to iron in the furnace spectrum, the classification would be altered only in a few cases by moving Class IV lines into Class V.

From the furnace material available, it is usually easy to tell in what group of the foregoing classification a line belongs. A few lines are on the border between Classes I A and I B, since the distinction depends mainly on the arc intensity. A decision between Classes IV and V is sometimes difficult for weak arc lines, but for such lines the difference is not usually important. The distinction is clear and valuable when we have a strong arc line that may be brought out readily (Class IV) or only with great difficulty (Class V) at the highest furnace temperature.

For some purposes a grouping of lines according to the temperature at which they first appear may be useful. In that case, Classes I A, I B, and II may be regarded as low-temperature lines, Class III as belonging to medium, and Classes IV and V to high temperature. This grouping leaves out of account the rate of increase with temperature, to show which is one of the main objects of the present work.

THE DETECTION OF BLENDS

It was naturally of great importance to determine how far the observed intensity of furnace lines might be affected by blends with lines belonging to foreign substances. The most disturbing elements, whose stronger lines appeared with those of iron in the furnace, were chromium, manganese, titanium, and vanadium, the two latter being given by the Acheson graphite. Fortunately, furnace spectra were available for these elements on the same scale as for iron, so that in the case of a suspected blend, it was a simple matter to see whether the furnace spectrum of the foreign substance gave that line of sufficient strength to appear when only a small quantity of the element was present as an impurity. When the furnace line of iron was probably affected in this way, the nature of the blend is given in the "Remarks" column of Table I. In the case of some blends it was not necessary to leave the intensity of the iron line wholly doubtful. For example, a low-temperature iron line is blended with the chromium line λ 5204.680, one of the strongest in that spectrum. The chromium line, however, is one of three which are affected similarly in any given source. From a furnace plate for chromium the strength of this line relative to the other two could be seen, so that on the iron plate it was possible to tell closely how much of the blend was due to the chromium line. The large scale of the second-order spectrum was useful in separating lines frequently blended with lower dispersion, especially for iron lines occurring in the carbon flutings which are always troublesome at high temperature.

EXPLANATION OF THE TABLE

In Table I the wave-lengths in the first column are those of Rowland. The second column gives the intensities of these lines in the arc, estimated from spectra taken on the same plate with some of the best furnace spectra. The intensities were estimated on the same plan as for the furnace spectra. The large range of intensity, together with the low values for some lines, results from the choice of an arc spectrum not very strongly exposed, so that the contrasts are distinct and the weaker lines faint. A line graded as low as 2 is a moderately strong line in a fully exposed arc spectrum. All arc lines above a certain minimum strength are included in the table, whether they appear in the furnace or not, this minimum being determined by the fact that some lines as weak as this (usually of Class I A) do appear in the furnace spectrum. The arc lines listed are strong enough to be considered in any general treatment of the arc spectrum, and their action in the furnace is of interest.

The method of grading the furnace lines has been given. For both arc and furnace, the standard spectra to the violet of λ 4700 were obtained on a Seed "27" plate (old emulsion), and those for the remainder of the spectrum on plates or films bathed with the three-dye solution. The intensities between λ 4500 and λ 4700 and in the red region are low on an absolute scale by reason of decreased sensitiveness of the plates, but arc and furnace spectra are affected alike. The letter *n* in connection with the arc intensity denotes that the line belongs to the class of "nebulous" lines which show a large width in proportion to their density, while *r* and *R* indicate respectively that the line is partially or completely reversed. The approximate values of the three temperatures are given on p. 6.

TABLE I

Temperature Classification of Iron Lines

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
3884.518	3	1	..	..	IV	
3885.657	5	3	..	..	IV	
3886.434	40*R*	40*R*	40*R*	25	I B	
3887.196	15	15	15	10	I B	
3888.671	20	10	9	6	II	
3888.971	3	..	..	..	V	
3890.986	2	1	..	..	IV	
3892.069	3	..	..	..	V	
3893.542	7	3	..	..	IV	
3895.803	25*r*	20*r*	20	12	I B	
3898.032	8	1	..	..	V	
3898.151	10	8?	6?	4	I B?	Blend with *V* which disturbs at medium and high temperature. Probable intensity of *V* line subtracted
3899.171	2	1	..	..	IV	
3899.850	30*R*	30*R*	25	14	I B	
3900.681	2	..	..	..	V	
3903.090	20	12?	10?	6	II	Blend with moderately strong *Cr* line
3904.052	5	2	..	..	IV	
3906.628	8	15	15	9	I B	
3906.890	2	..	..	..	V	
3908.077	4	2	..	..	IV	
3909.976	3	..	..	..	V	
3913.775	4	3	..	..	IV	
3916.879	6	Tr.	..	..	V	
3917.324	8	10	10	4	I B	
3918.464	3	2	..	..	IV?	Not resolved on plates strong enough to give lines in furnace
3918.563	4					
3918.789	6	1	..	..	V	
3919.208	3	1	..	..	IV	
3920.410	20*r*	20*r*	20	15	I B	
3923.054	25*R*	30*R*	25	15	I B	
3925.790	4	1	..	..	IV	
3926.086	6	2	..	..	IV	
3928.075	30*R*	30*R*	25	15	I B	
3930.450	25*R*	35*R*	30	18	I B	
3932.785	4	1	..	..	IV	
3935.965	8	3?	..	..	IV?	Furnace line may be *Ba*
3937.479	3	1	..	..	IV	
3941.025	5	10?	9?	4?	I A?	May be partly *Sr* and *Co*
3942.586	6	1	..	..	V	

TABLE I—*Continued*

λ (ROWLAND)	ARC	FURNACE			CLASS	REMARKS
		High Temp.	Medium Temp.	Low Temp.		
3943.489	2	1	..	..	IV	
3945.033	3	Tr.	..	..	IV	
3945.260	4	Tr.	..	..	IV	
3947.142	4*n*	Tr.	..	..	IV	
3947.675	5	Tr.	..	..	V	
3948.246	6*n*	Tr.	..	..	V	
3948.925	10	..	..	..	V	
3950.102	10	8	4	Tr.	III	
3951.311	9	1	..	..	V	
3952.754	8	2	..	..	IV	
3953.303	4	Tr.	..	..	V	
3956.099	2	..	..	..	V	
3956.603	9	..	..	..	V	
3956.819	12	8	4	Tr.	III	
3957.177	4*n*	Tr.	..	..	IV?	Furnace line may be *Ca*
3963.252	6*n*	Tr.	..	..	V	
3964.663	3	..	..	..	V	
3966.212	10	10	8	2	II	
3966.778	10*n*	2	1	..	IV	
3967.570	8	1	..	..	V	
3968.114	4*n*	..	..	..	V	
3969.413	30	16	12	8	II	
3970.540	4	Tr.	..	..	IV	
3971.475	9	4	2	..	III	
3973.796	3	..	..	..	V	
3976.770	4	Tr.	..	..	IV?	Furnace line may be *Cr*
3977.891	12	9	4	1	II	
3981.917	7	12?	10?	2	I B	Close blend with *Ti* line which may predominate in furnace spectrum at medium and high temperature
3984.113	10	4	2	..	III	
3985.539	3	..	..	..	V	
3986.321	5	..	..	..	V	
3990.525	2	..	..	..	V	
3994.265	2	..	..	..	V	
3996.140	4	1	..	..	IV	
3997.115	2	..	..	..	V	
3997.547	15	7	2	..	III	
3998.205	10	4?	2?	..	III?	May be partly *Co*
4000.611	2	..	..	..	V	
4001.814	5	3	2	..	III	
4003.912	2	..	..	..	V	
4005.408	25	15	12	9	II	
4006.464	3	..	..	..	V	
4006.776	2	..	..	..	V	

TABLE I—*Continued*

λ (ROWLAND)	ARC	FURNACE			CLASS	REMARKS
		High Temp.	Medium Temp.	Low Temp.		
4007.429	6	2	Tr.	..	III	
4009.864	10	9?	6?	1	II?	Furnace line chiefly *Ti*
4013.964	2	..	..	..	V	
4014.677	10	3	1	..	III	
4017.308	6	2	1	..	III	
4022.018	12	6	2	..	III	
4024.881	6*n*	..	..	..	V	
4029.796	3*n*	..	..	..	V	
4032.117	4	..	..	..	V	
4032.789	4	8	6	1	III?	Arc intensity low for Class III. Well separated from *Mn* 4033.224
4040.792	4	..	..	..	V	
4044.056	5*n*	..	..	..	V	
4044.766	6	2	..	..	IV	
4045.975	60*r*	30	22	15	II	
4055.023	3	..	..	..	V	
4055.189	3	..	..	..	V	
4057.499	2	..	..	..	V	
4058.372	4*n*	..	..	..	V	Blend with *Co*
4058.915	3	..	..	..	V	
4059.872	3	..	..	..	V	
4062.599	10	4	2	..	III	
4063.759	45	20	15	12	II	
4067.139	6	2	..	..	IV	May be partly *Cr*
4067.429	4	2	..	..	IV	
4068.137	8*n*	2	..	..	IV	May be partly *Mn*
4070.930	5*n*	1	..	..	IV	
4071.908	40	18	12	10	II	
4073.921	4*n*	1	..	..	IV	
4074.947	5	1	..	..	IV	
4076.792	8*n*	2	..	..	IV	
4078.515	4	2	..	..	IV	May be partly *Ti*
4079.996	4	1	..	..	IV	
4080.368	2*n*	Tr.	..	..	IV	
4084.647	6	1	..	..	V	
4085.161	4	1	..	..	IV	
4085.467	4	1	..	..	IV	
4096.129	4	2	1	..	III	
4098.335	4*n*	1	..	..	IV	
4100.901	3	10	8	3	I A	
4104.288	3	..	..	..	V	
4107.649	12	4	2	..	III	
4109.953	9	?	..	..	V	Weak if present at all in furnace. Close to strong *V* line at 4109.905
4113.117	3*n*	..	..	..	V	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4114.606	5	2	Tr.	. .	IV	
4118.708	15	2	1	. .	IV	
4120.368	5	2	. .	. .	IV	
4121.963	5	1	. .	. .	IV	
4122.673	4	1	. .	. .	IV	
4126.344	3*n*	. .	. .	. .	V	
4127.767	7	2?	. .	. .	IV	Furnace line partly *Ti*
4127.957	3*n*	. .	. .	. .	V	
4132.235	25	15	15	8	II	Furnace line very slightly affected by *V* blend
4133.062	8	3	. .	. .	IV	
4134.840	12	2?	. .	. .	IV	Furnace line partly *V*
4137.156	7	Tr.	. .	. .	V	
4140.089	2	6	4	2	I A	
4143.572	15	5	2	. .	III	
4144.038	30	15	12	10	II	
4147.836	10	10	8	2	I B	
4149.533	5*n*	. .	. .	. .	V	
4152.343	4	10	8	2	I A	
4154.071	10*n*	2	. .	. .	IV	
4154.667	12	4	2	. .	III	
4154.976	9*n*	1	. .	. .	V	
4156.970	12	4	2	. .	III	
4157.948	8*n*	1	. .	. .	V	
4158.959	5*n*	Tr.	. .	. .	V	
4171.068	5	1	. .	. .	V	
4172.296	5	1	. .	. .	V	
4172.923	4	9	9	3	I A	
4173.480	2	Tr.	. .	. .	IV	
4174.095	2	6	6	2	I A	
4175.082	5	10	10	5	I A	
4175.806	10	3	1	. .	III	
4176.739	7*n*	2	. .	. .	IV	Blends with high-temperature line of *Mn*. Furnace line probably *Fe*
4177.698	4	10	10	4	I A	
4181.919	15	6	3	1	III	
4182.548	4	1	. .	. .	IV	
4185.058	10	3	1	. .	III	
4187.204	20	10	7	2	II	
4187.943	20	10	7	2	II	
4191.595	15	9	6	1	III	
4195.492	5	1	. .	. .	V	
4196.372	4	1	. .	. .	IV	
4198.494	20	10	7	1	III	
4198.800	4*n*	Tr.	. .	. .	V	
4199.267	20	7	3	Tr.	III	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4200.148	1	9	8	4	I A	
4201.089	3*n*	..	..	..	V	
4202.198	30	18	12	9	II	
4204.101	10	3	1	..	III	
4206.862	3	12	12	8	I A	
4207.291	4	Tr.	..	..	V	
4208.766	3*n*	..	..	..	V	
4210.494	15	8	4	Tr.	III	
4213.812	5	2	..	..	IV	
4215.581	2	1	..	..	IV	
4216.351	8	10	12	8	I B	
4217.720	7*n*	1	..	..	V	May be partly *Cr*
4219.516	12	2	1	..	IV	
4220.509	4	1	..	..	IV	
4222.382	12	8	4	Tr.	III	
4224.337	6*n*	1	..	..	V	
4224.673	3*n*	..	..	..	V	
4225.619	6*n*	1	..	..	V	
4226.116	3	Tr.	..	..	V	
4226.584	3	Tr.	..	..	V	
4227.606	30	5	3	..	III	
4232.887	1	8	7	3	I A	
4233.772	18	9	6	1	III	
4236.112	25	10	8	2	II	
4238.188	4	Tr.	..	..	V	
4238.970	10*n*	2	1	..	IV	
4239.890	3	1	..	..	IV	
4240.014	2	3	2	..	I B ?	Always faint. Would probably show at low temperature with long exposure
4245.422	6	3	2	1	II	
4246.251	3	..	..	..	V	
4247.591	12	3	2	..	III	
4248.384	4	Tr.	..	..	V	
4250.287	25	10	5	1	III	
4250.945	25	15	12	8	II	
4258.477	2	10	8	6	I A	Probably chiefly if not wholly due to *Fe*. A weak *Mn* line is given by Hasselberg at 4258.48 which appears faintly in *Mn* furnace but may be due to *Fe* which is present when *Mn* is used
4260.640	35	15	10	2	III	
4267.122	3	1	..	..	IV	

TABLE I—*Continued*

λ (ROWLAND)	ARC	FURNACE			CLASS	REMARKS
		High Temp.	Medium Temp.	Low Temp.		
4267.985	5	1	..	..	V	
4268.915	2	Tr.	..	..	IV	
4271.325	20	10	5	2	III	
4271.934	35	20	15	12	II	
4282.565	12	10	7	3	I B	
4285.605	3	1	..	..	IV	
4291.630	4	10	10	8	I A	
4294.301	15	12	12	6	I B	
4299.410	18	9	5	2	II	
4305.614	3	Tr.	..	..	IV	
4308.081	35	20	15	10	II	
4309.541	4	1	..	..	IV	
4315.262	10	8	6	1	III	
4325.939	35	20	15	10	II	
4327.274	3	..	..	..	V	
4337.216	10	10	9	4	I B	
4351.711	3	..	..	..	V	
4352.908	9	8	8	2	I B	
4358.670	3	Tr.	..	..	IV	
4367.749	5	Tr.	..	..	V	
4368.071	2	4	3	1	I A	
4369.941	7	3	1	..	III	
4376.107	9	15	15	10	I B	Wider in proportion to density than 4415.293
4383.720	45*r*	30	20	12	II	
4388.057	3	Tr.	..	..	IV	
4388.571	4*n*	Tr.	..	..	IV	
4389.413	2	10	8	5	I A	
4391.123	4	Tr.	..	..	IV	
4404.927	30	20	15	9	II	
4407.871	5	3?	?	Tr.	III?	Allowance made for blend with *V*
4408.582	6	4	?	Tr.	III?	Blended with *V* except on one plate
4415.293	20	15	12	7	II	
4422.741	6	2	1	..	IV	
4427.482	10	12	12	9	I B	Wider in proportion to density than 4415.293
4430.785	6	4	2	1	II	
4433.390	3*n*	Tr.	..	..	IV	
4435.321	2	10	8	6	I A	Just resolved from *Ca*
4442.510	12	9	5	1	III	
4443.365	7	2	Tr.	..	IV	
4447.892	9	8	5	2	II	
4454.552	5	2	1	..	III	
4459.301	10	8	4	2	II	
4461.818	8	12	12	10	I B	
4466.727	12	12	10	6	I B	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4469.545	5*n*	1	. .	. .	IV	
4476.185	10	4	2	. .	III	
4482.338	4	15	15	10	I B	Not fully resolved on most plates. 4482.338 seems about 4 times strength of 4482.438. In arc 4482.338 behaves as I A line and 4482.438 as I B
4482.438	6					
4484.392	4	. .	. .	. .	V	
4489.911	3	12	12	8	I A	
4494.738	12	9	5	2	II	
4525.314	5*n*	1	. .	. .	IV ?	Furnace line may be *V*
4528.798	18	12	9	3	II	
4531.327	8	10	7	4	I B	
4548.024	4	. .	. .	. .	V	
4556.306	4*n*	. .	. .	. .	V	
4592.840	5	8	6	2	I B	
4603.126	9	10?	9?	4?	I B ?	Furnace line may be largely *Li*
4607.831	3*n*	. .	. .	. .	V	
4611.469	5*n*	2	1	. .	III	
4613.386	2*n*	. .	. .	. .	V	
4619.468	3*n*	*	. .	. .	IV	
4625.227	3	*	. .	. .	IV	
4633.100	2	5	3	. .	III ?	Weak in arc for Class III
4637.685	3	*	. .	. .	IV	
4638.193	3	*	. .	. .	IV	
4647.617	6	*	1	. .	IV	
4654.672	5	?	?	1	II ?	Not fully resolved. 4654.672 blends with fluting line at high temperature
4654.800	5	. .	. .	. .	V	
4667.626	6	. .	. .	. .	V	
4668.243	6	*	. .	. .	IV	
4679.027	7	. .	. .	. .	V	
4691.602	6	*	. .	. .	IV	
4707.457	8	*	. .	. .	IV	
4710.471	5	*	. .	. .	IV	
4727.582	3*n*	*	. .	. .	IV	
4728.732	3*n*	*	. .	. .	IV	
4733.779	4	*	4	1	I B ?	
4736.963	12	*	*	2?	II ?	Blend with head of *C* band and intensity doubtful
4741.718	3	. .	. .	. .	V	

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* Occurrence uncertain on account of strong carbon bands at high temperature, but *Fe* lines are weak in furnace, if present at all. Provisionally placed in Class IV.

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4745.992	3*n*	..	..	..	V	
4768.595	3*n*	..	..	..	V	
4773.007	3	3	2	..	III	
4787.003	5	1	..	..	IV?	Furnace line may be *V*
4789.849	7	..	..	..	V	
4859.928	15	6	2	..	III	
4871.512	25	9	3	..	III	Furnace line may be slightly affected by *V* blend
4872.332	20	7	2	..	III	
4878.407	12	5	2	..	III	
4885.620	2	..	..	..	V	
4890.948	25	8	2	..	III	
4891.683	50	12	3	..	III	
4903.502	12	4	1	..	III	
4919.174	30	8	2	..	III	
4920.685	60	12	4	Tr.	III	
4924.956	3	..	..	..	V	
4938.997	10	3	..	..	IV	
4939.868	4	10	8	5	I B	
4946.568	4	5	..	..	IV	
4957.480	20	5	2	..	III	
4957.785	60	12	6	1	III	
4966.270	8	1	..	..	V	
4973.281	3	..	..	..	V	
4978.785	2	..	..	..	V	
4982.682	8*n*	..	..	..	V	
4983.433	5*n*	..	..	..	V	
4984.028	6*n*	..	..	..	V	
4985.432	7	Tr.	..	..	V	
4985.730	7	1	..	..	V	
4994.316	8	9	9	4	I B	
5002.044	12	1	..	..	V	
5005.896	10	..	..	..	V	
5006.306	20	4	1	..	III	
5012.252	12	10	9	8	I B	
5015.123	10	..	..	..	V	
5022.414	6	..	..	..	V	
5027.305	5*n*	..	..	..	V	
5028.308	4	..	..	..	V	
5041.255	7	7	6	3	I B	
5041.936	10	7	4	1	III	Blend with *Ca* probably has little effect on furnace intensity
5050.008	15	12	2	..	III	
5051.825	10	10	8	6	I B	
5065.207	6*n*	?	..	..	V	Concealed by *C* if present

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
5068.944	10	. .	. .	. .	V	
5074.932	10*n*	. .	. .	. .	V	
5079.409	6	3	Tr.	. .	IV	
5079.921	4	6?	4	2	I B	Blend with *C* at high temperature
5083.518	7	10?	7	4	I B	Blend with *C* at high temperature
5098.885	8	4	Tr.	. .	IV	
5107.619	6	4	3	2	I B	Blend on some plates makes estimates difficult
5107.823	8	3	2	1	II	
5110.574	10	8?	10	15	I B	Remarkably strong at low temperature. Blend with *C* at high temperature
5123.899	6	9?	5	3	I B	Blend with *C* at high temperature
5125.300	6*n*	. .	. .	. .	V	
5127.533	5	8?	4	2	I B	Blend with *C* at high temperature
5133.870	20*n*	?	. .	. .	V	Blend with *C*. Very weak if present
5137.558	6*n*	. .	. .	. .	V	
5139.427	10	4?	. .	. .	IV	Blend with *C* at high temperature
5139.644	20	4?	Tr.	. .	IV	Blend with *C* at high temperature
5143.111	6	5	4	3	I B	
5151.020	6	5	4	2	I B	
5152.087	4	6?	3	1	I B	Blend with *C* at high temperature
5162.449	10*n*	?	. .	. .	IV?	Blend with *C* at high temperature. Probably present, but weak
5166.454	4	8	8	10	I A	Blend with weak *Cr* line which probably has little effect
5167.678	40	12	9	7	II	
5169.069	4	8	8	10	I A	
5171.778	20	10	6	3	II	
5191.629	20	4	. .	. .	IV	
5192.523	30	5	Tr.	. .	IV	
5195.113	10	9	5	2	I B	
5198.888	4	2	. .	. .	IV	
5202.439	8	4	1	. .	IV	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
5204.768	2	6?	6?	7?	I A	Blend with *Cr* 5204.680, the probable intensity of which is subtracted
5208.776	7	2	..	..	IV	
5215.353	6	2	..	..	IV	
5216.437	10	6	3	1	II	
5217.552	5	1	..	..	V	
5225.695	1	6	5	5	I A	
5227.043	15	2	..	..	IV	
5227.362	40	12	10	6	II	
5230.030	5*n*	1	..	..	V	
5233.122	40	7	2	Tr.	III	
5242.658	4	1	..	..	IV	
5247.229	1	5	6	5	I A	
5250.385	1	5	6	5	I A	
5250.817	6	3	Tr.	..	IV	
5255.121	1	8	8	6	I A	
5263.486	8	1	..	..	V	
5266.738	30	5	1	..	IV	
5269.723	60	25*R*	20	20	I B	
5270.558	30	12	10	5	II	
5273.558	4	1	..	..	IV	
5281.971	10	2	..	..	IV	
5283.802	18	3?	..	..	IV	Furnace line may be partly *Ti*
5302.480	10	1	..	..	V	
5307.541	2	3	1	..	III?	Difficult to classify. Arc intensity low for Class III
5324.373	30	6	1	..	IV	
5328.236	50	25*r*	20	20	I B	
5328.696	15	12	10	3	II	
5333.089	4	5	2	1	I B?	Strengthens rapidly for Class I B
5340.121	12	2	..	..	V	
5341.213	20	10	8	3	II	
5365.069	15*n*	Tr.	..	..	V	
5365.596	3	Tr.	..	..	V	
5367.669	20*n*	1	..	..	V	
5370.166	25*n*	1	..	..	V	
5371.734	50	25	20	20	I B	
5383.578	35*n*	2	..	..	V	
5393.375	10	3	Tr.	..	IV	
5397.344	40	20	18	18	I B	
5404.357	30*n*	2	..	..	V	
5405.989	40	20	18	18	I B	
5411.124	15*n*	Tr.	..	..	V	
5415.416	35*n*	2	..	..	V	
5424.290	45*n*	3	..	..	V	
5429.911	40	20	18	18	I B	

TABLE I—*Continued*

λ (ROWLAND)	ARC	FURNACE			CLASS	REMARKS
		High Temp.	Medium Temp.	Low Temp.		
5434.740	30	18	15	15	I B	
5445.259	15*n*	Tr.	..	..	V	
5447.130	40	20	18	18	I B	
5455.834	40	20	18	18	I B	
5463.494	10*n*	..	..	..	V	
5476.778	10	3	..	..	IV	
5497.735	15	15	12	5	I B	Compare with other I B lines to violet
5501.683	12	12	10	4	I B	
5507.000	18	18	15	6	I B	
5555.122	4	..	..	..	V	
5563.824	3	..	..	..	V	
5565.931	4	..	..	..	V	
5569.848	20	4?	..	..	IV	Blend with *C* at high temperature
5573.075	30	5?	..	..	IV	Blend with *C* at high temperature
5576.320	10	2?	..	..	IV	Blend with *C* at high temperature
5586.991	40	6	Tr.	..	IV	
5598.524	4	?	..	..	IV?	Blend with *C* at high temperature
5603.186	10	2?	..	..	IV	Blend with *C* at high temperature
5615.877	50	8	1	..	IV	
5624.769	10	3?	..	..	IV	Blend with *C* at high temperature. May be affected by *V* blend
5638.488	3	..	..	..	V	
5655.715	4	..	..	..	V	
5659.052	10	3	..	..	IV	
5662.744	6	1	..	..	V	
5701.772	7	5	..	..	III?	Would be expected to show at moderate temperature on strong plates
5709.601	10	3	..	..	IV	
5753.344	5	..	..	..	V	
5763.218	10	Tr.	..	..	V	
5859.809	5	..	..	..	V	
5862.582	8	..	..	..	V	
5884.028	4	..	..	..	V	
5905.895	3*n*	..	..	..	V	
5914.335	8	..	..	..	V	
5930.406	8	..	..	..	V	
5934.881	5	..	..	..	V	
5952.943	3	..	..	..	V	
5975.575	4	..	..	..	V	
5977.007	5	..	..	..	V	
5983.908	6	..	..	..	V	
5985.040	8	2	..	..	IV	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
5987.290	6	. .	. .	. .	V	
6003.239	8	. .	. .	. .	V	
6008.785	9	. .	. .	. .	V	
6020.401	10*n*	. .	. .	. .	V	
6024.281	15	. .	. .	. .	V	
6027.274	4	. .	. .	. .	V	
6042.315	2	. .	. .	. .	V	
6056.227	4	. .	. .	. .	V	
6065.709	15	7	4	. .	III	
6078.710	4*n*	. .	. .	. .	V	
6102.392	5	. .	. .	. .	V	
6103.400	3	. .	. .	. .	V	
6136.829	20	10	6	. .	III	
6137.915	18	7	3	. .	III	
6141.938	4	. .	. .	. .	V	
6157.945	4	. .	. .	. .	V	
6170.730	4*n*	. .	. .	. .	V	
6173.553	3	3?	1	. .	III	Blend with *C* at high temperature
6191.779	20	10	7	1	II	Weak at low temperature for Class II
6200.527	4	1	. .	. .	IV	
6213.644	5	4	2	. .	III	
6219.494	6	5	2	. .	III	
6230.943	25	12	8	. .	III	Blend with *V* which probably has little effect
6232.856	5	. .	. .	. .	V	
6246.535	15	1	. .	. .	V	
6252.773	20	9	5	. .	III	
6254.456	6	4	2	. .	III	
6256.572	4	2	1	. .	III	
6265.348	6	5	3	. .	III	
6280.833	2	9	7	3	I A	
6291.184	3*n*	. .	. .	. .	V	
6298.007	5	4	2	. .	III	
6301.718	15	2	Tr.	. .	IV	
6302.709	6	. .	. .	. .	V	
6318.239	10	7	3	. .	III	
6322.907	5	2	1	. .	III	
6335.554	10	8	4	. .	III	
6337.048	12	1	. .	. .	V	
6344.371	2	1	Tr.	. .	III	
6355.246	4	2	1	. .	III	
6358.898	3	9	7	3	I A	
6380.958	3	. .	. .	. .	V	
6393.820	15	12	8	Tr.	III	
6400.217	25	4	2	. .	III	
6408.233	8	. .	. .	. .	V	
6411.865	12	2	1	. .	IV	
6420.169	5*n*	. .	. .	. .	V	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
6421.570	10	8	5	..	III	
6431.066	10	10	7	Tr.	III	
6462.965	5	?	?	?	?	Occurrence in furnace uncertain on account of blend with low temperature *Ca* line
6469.408	2	..	..	..	V	
6475.846	3	1	..	..	IV	
6482.098	4	1	..	..	IV	
6495.213	25	15	10	2	II	
6546.479	10	7	3	..	III	
6569.460	5	..	..	..	V	
6575.270	2	..	..	..	V	
6593.161	10	6	2	..	III	
6594.121	4	3	..	..	IV	
6609.360	4	2	..	..	IV	
6633.995	7*n*	..	..	..	V	
6663.701	8	4	..	..	IV	
6678.235	12	9	3	..	III	
6750.407	6	3	..	..	IV	
6828.850	4	..	..	..	V	
6841.598	4	..	..	..	V	
6843.913	4	..	..	..	V	
6855.419	5	..	..	..	V	
6945.477	4	2	..	..	IV	
6979.120	3	1	..	..	IV	
7187.645	5	..	..	..	V	These lines are really stronger than indicated, as plate loses sensitiveness rapidly in this region
7207.715	3	..	..	..	V	

DISCUSSION OF THE CLASSIFICATION

An examination of Table I shows a considerable variety as to the rate of growth among lines placed in the same class; but there is little to be gained by increasing the number of classes to cover these variations. There appears in all classes to be a continuous change in the intensities of furnace lines with temperature, the several classes being distinguished by the rate of change shown by each. As the scale has been arranged in Table I, the low-temperature lines of Classes I A and I B strengthen slowly or remain nearly the same for the three temperatures. As a rule, there is little difference between medium and high temperature for these lines. If the intensities of Class II lines had been graded so as to show approximate equality for the three temperatures, the lines of Classes I A and I B would have shown a gradual weakening as the temperature rises. This point of view, however, does not seem to me to represent the true state of affairs as well as that adopted in the arrangement of Table I, which shows the Class II lines rapidly increasing in strength while the lines of Classes I A and I B about hold their own. Class II and Class III lines usually show a regular change of intensity with temperature, but many variations occur in the rate of change for individual lines.

If we regard the arc conditions as equivalent to a higher-temperature stage than that of the furnace, it is necessary to assume that large changes may occur in the temperature interval separating the two sources, and of very different magnitudes for different lines. However, lines in the same class, when near together in the spectrum so that the intensities were estimated from the same set of plates, show a fair degree of correspondence between the rate of change in the furnace and that for the interval between furnace and arc. This is best seen for lines in Classes II and III. So that, making allowance for difficulties in forming a concordant scale of intensities for arc and furnace lines, it may be said that if each class maintains the rate of change which it shows through the temperature range of the furnace observations (about 800°), it would be expected to reach an arc intensity of the order of that observed.

To account for the behavior of Class I A lines on the basis of a continuous change with temperature, we must adopt a scale of gradation such that these lines will diminish in intensity through the furnace range if they are to reach the weakness shown in the arc, where many of them, such as $\lambda\lambda$ 4258.477, 5225.695, and 5255.121, can only be given an intensity comparable with the furnace line by exposures of the arc so long as to give very high intensities to the lines of other classes. As compared with the rest of the spectrum, the arc is certainly at a great disadvantage in producing these lines. It is an interesting question whether the furnace would show them relatively as weak if it could be brought to the temperature of the arc. Judging from the way the lines of Class I A maintain their strength through the range of furnace temperatures which has been produced, this seems unlikely. With two or three exceptions, the lines of Class I A have not been considered in investigations on the variation of arc and spark lines, doubtless because of their faintness in these sources. Their appearance in the flame and core of the arc is important and will be described later in this paper.

The high furnace temperature required to give the red end of the spectrum is noteworthy. The low intensity of the red lines is due in part to the decreased sensitiveness of the plates for this region, but very long exposures with both the large and small spectrographs have failed to give any red lines of iron at low temperature, except traces of the strongest arc lines and the two lines λλ 6280.833 and 6358.898 belonging to Class I A. At medium and high temperatures a large number of red lines were obtained. This behavior has placed almost all of these lines in classes not lower than III. The relative ease with which the blue end of the spectrum appears shows that the emission of the line spectrum does not follow closely the laws for an incandescent solid. This was well shown in a two-hour exposure with the very bright 1-meter concave grating, a bathed film being used. The furnace temperature measured about 1800° C. The exposure was so long that the weak continuous spectrum given by the vapor (probably largely through light from the wall of the tube reflected by the vapor particles) was able to impress itself on the plate distinctly in the red and orange. Iron lines were almost entirely lacking for this region, while they were plentiful in the blue where the continuous spectrum was very weak. This behavior, however, does not present an exception to any known law of spectral distribution, since no series have been recognized among iron lines, and a resemblance to the intensity gradations for an incandescent solid can be expected only for lines thus related.

Other notable groups of strong arc lines which are given only at the higher furnace temperatures occur at λ 4860 to λ 4960 and λ 5570 to λ 5625. The "nebulous" lines, indicated by *n* in connection with the arc intensity, are among the most difficult to obtain in the furnace. Some of the best examples occur between λ 5360 and λ 5460. By long exposure at high temperature it was possible to obtain all of these distinctly, so that probably similar lines throughout the spectrum can be obtained under the same conditions. They usually belong clearly in Class V.

LINES WHICH MAY BE USED AS CRITERIA OF TEMPERATURE CONDITIONS

In sources for which a difference in temperature is considered to have a large part in the observed variations in the spectrum, a comparison of the intensities of lines near together which show a very different behavior in the furnace will usually show, in a general way at least, how the temperatures of the sources are related. Many pairs and groups of lines in Table I may be used in this way, but the following (Table II, p. 30) are suggested as especially suitable. The two lines in each case show a decided difference, both as to the temperature at which they appear and the rate of their change.

Some of the pairs in Table II are especially useful in deciding whether a given source more nearly resembles the arc or the furnace. Cases in which a Class I A line is paired with a line of Class II or Class III are favorable for this purpose. The behavior of the three lines λλ 5498, 5502, 5507 as compared with the strong I B lines from λ 5456 to λ 5269 is peculiar. These three lines are weak at low temperature but increase rapidly in the interval covered by the three furnace temperatures. The other I B lines in this region are strong at low temperature and increase slowly, but show a much greater increase in the interval between furnace and arc than is shown by the group of three, which would seem to belong in a class between Classes I B and II. If it were not for their relatively low intensity in the arc, the three lines would belong clearly in Class II. λ 5333.089 shows a very similar behavior in furnace and arc.

PRELIMINARY ACCOUNT OF THE ULTRA-VIOLET FURNACE SPECTRUM

A set of furnace photographs of the ultra-violet for which the iron arc spectrum reaches as far as λ 2300 has been made with the

1-meter concave grating already described. In most respects these are very satisfactory, but as a concave grating spectrograph of 15 ft. radius is under construction, it will be desirable to supplement them by large-scale photographs covering at least the portion where lines are most numerous in order to reduce the uncertainties as to blends and show more clearly the character of the lines. As the small spectrograph is adjusted, the second order can be followed from λ 4000 to about λ 2800, from which point the greater strength

TABLE II

NEIGHBORING LINES WHICH ARE DIFFERENTLY AFFECTED IN THE FURNACE

λ	Class	λ	Class
3950.102	III	4459.301	II
3951.311	V	4461.818	I B
3966.212	II	4489.911	I A
3966.778	IV	4494.738	II
4100.901	I A	4528.798	II
4107.649	III	4531.327	I B
4177.698	I A	4919.174	III
4181.919	III	4939.868	I B
4199.267	III	5050.008	III
4202.198	II	5051.825	I B
4206.862	I A	5166.454	I A
4210.494	III	5171.778	II
4216.351	I B	5225.695	I A
4219.516	IV	5233.122	III
4232.887	I A	5341.213	II
4233.772	III	5371.734	I B
4250.287	III	6246.535	V
4250.945	II	6252.773	III
4271.325	III	6280.833	I A
4271.934	II	6301.718	IV
4260.640	III	6335.554	III
4308.081	II	6337.048	V
4291.630	I A	6355.246	III
4294.301	I B	6358.898	I A
4415.293	II	6393.820	III
4427.482	I B	6411.865	IV

of the first order is an advantage for the very short wave-lengths. The scale in the second order being 8.5 Å per mm and the definition very sharp, the spectrum can be examined to good advantage under the microscope of a measuring machine with fairly high power. The resolving power of the grating is sufficient to separate sharp lines at λ 2800 which are 0.15 Å apart. While postponing the detailed publication of the ultra-violet spectrum, a few of the leading features may be given here.

At high temperature, the line of shortest wave-length thus far photographed has been λ 2463. At medium temperature, prolonged exposures have yielded lines beginning at λ 2706; while the lower furnace temperature has thus far failed to show any lines of wave-length less than λ 3440. These limits are interesting as showing the gradual extension into the ultra-violet with increasing temperature. As absolute limits for a given temperature, they would probably be modified somewhat by a quartz prism apparatus or by a grating reflecting the short waves more strongly. Photographic emulsions more sensitive to this region would also give an extension if the furnace vapor does not absolutely cease to radiate at the limits observed. At the highest temperatures I have suspected that absorption by the vapor in the furnace tube may act in shortening the ultra-violet spectrum. The generation of vapors of all kinds, including those from carbon and the tube impurities is then very vigorous and the extension toward shorter wave-lengths has varied for different runs of the furnace made at approximately the same high temperature. For medium and low temperatures the results in this regard have been more consistent. This feature makes more difficult the comparison of temperatures between the furnace and any other source, based on the extension into the ultra-violet.

The classification adopted in Table I would have a different meaning if applied to the extreme ultra-violet, since there is an actual discontinuance the spectrum of at certain points according to the temperature employed. Thus the lines below λ 2700 would go into Classes IV and V, with a large addition of Class V lines which are given only in the arc for this region. From λ 2700 to λ 3440 numerous Class III lines would enter the list, while from λ 3440 into and through the visible region all of the classes would appear.

It was found when a graphite plug was placed in the middle of the furnace tube and the furnace heated to different temperatures that the extension of the continuous spectrum into the ultra-violet for each temperature varied in a way closely corresponding to that of the line spectrum; but when such continuous spectra were taken on the same film at low, medium, and high temperatures each of them reached at least 300 Å farther than it has been possible to obtain lines at the same temperature, even with much longer exposures than were used for the continuous spectra. The furnace tube with a plug at its center obviously approximates black-body conditions, and the inference is that the radiation of a black body is stronger than the emission of a line spectrum at the same temperature. Some experiments in which the furnace was charged with metallic calcium containing as impurities several other elements of low melting-points showed the same relation. As far as experiments have proceeded, the furnace never gives a bright line as far to the violet as the continuous spectrum from a plugged tube will easily extend at the same temperature.

A COMPARISON OF THE INTENSITY VARIATION SHOWN BY THE CORE AND THE FLAME OF THE IRON ARC

In the earlier work done at this observatory on the spectra of sun-spots,[1] the relative intensities of lines given by the core and by the outer envelope of the arc were compared and ascribed in the main to temperature differences. Some experiments at that time with a furnace of Moissan type in which a carbon tube containing iron was heated by an arc playing over its outer wall gave spectra resembling that of the outer arc vapors. The material obtained in the present work for a variety of furnace temperatures offered a means of testing the validity of the hypothesis as to the relative temperatures of arc vapors. A series of large-scale photographs was made with the image of the arc focused so as to give its cross-section on a long slit. The arc could be made to burn very steadily, the greenish core showing at the middle of the slit, while the flame vapors, gradually decreasing in luminosity, spread toward the end. The spectrum photographed records the intensity of each line as given by the vapor in a horizontal plane through the arc, about midway between the poles. The arc lines then show the following characteristics:

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[1] Hale, Adams, and Gale, *Contributions from the Mount Wilson Solar Observatory*, No. 11; *Astrophysical Journal*, **24**, 185, 1906.

1. The line is always most intense at its middle, where the radiation is given by two thicknesses of flame vapor, together with that of the core. From this point the line narrows, but at a rate which differs for different lines. The "short and long line" classification of Lockyer is based on this characteristic.

2. The ability of the cooler vapors of the flame to give a certain line is registered by the strength of the extensions from the center. This varies greatly for different lines and in general the distance from the center to which a line extends and the rate at which it strengthens from the end toward the center resemble, respectively, the stage of temperature at which a line appears in the electric furnace and the rapidity of its increase in strength with temperature.

This relation is shown in Fig. 1, the lower part of which represents by the shaded rectangles the relative strengths of the several classes at low, medium, and high temperature, while the upper portion gives sketches of typical lines of each class showing one-half of the line when the cross-section of the arc is projected on the slit in the manner described. The broken horizontal lines in the upper portion inclose parts of the spectrum line which may be considered as appearing in the core (reinforced by the superposed flame in the line of sight) and in the inner and outer portions of the flame vapors respectively. Photographs which give lines similar to those in this figure have been made by placing fine wires across the slit at the proper intervals.

Taking the several classes in turn, the I A lines are always weak in the arc, but they run some distance into the flame without much diminution of intensity. Judging from their appearance, very little of their strength is given by the central core of the arc. They do not, however, appear in the outermost vapors of the flame, as do the lines of Classes I B and II, the arc differing materially from the furnace in this respect. The furnace sometimes shows a I A line very similar at all temperatures to a neighboring I B line, while the latter is far stronger in the arc. Examples are λλ 4291.630 and 4294.301, also λλ 4489.911 and 4466.727.

Lines of Class I B and the stronger ones of Class II run farthest into the flame vapors but show a decided contrast in the way in which they thicken as they approach the core. Adjacent lines of Classes I B and II may extend the same distance into the flame, but the Class II lines will often be two or three times as strong as the other at the core. λλ 4415.293 and 4427.482 are good examples and there are many similar ones. This behavior in the arc

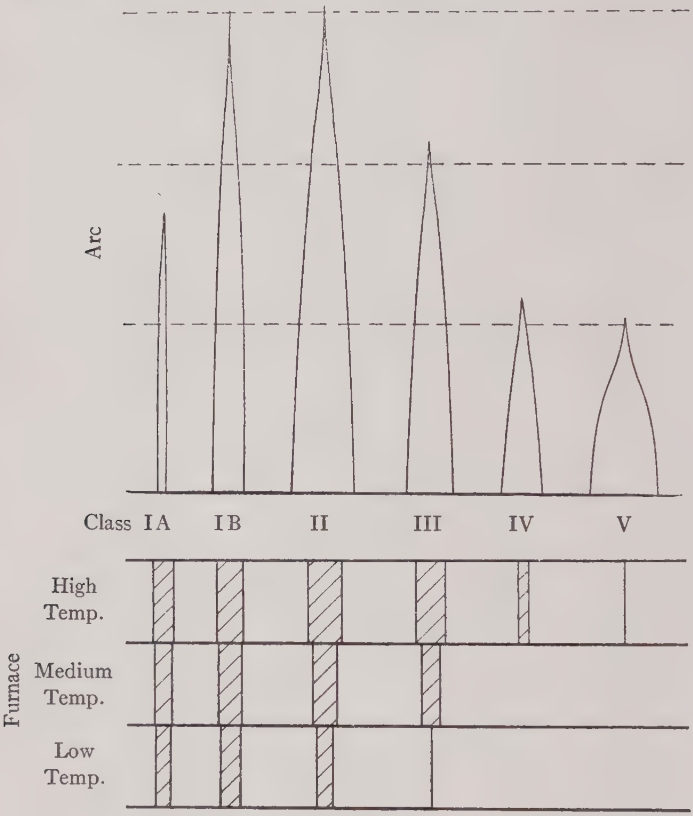

FIG. 1.—Comparison of relative intensities of furnace lines with the intensities of lines produced by different parts of the arc.

corresponds closely with that in the furnace, both being low-temperature lines as regards initial appearance, but the I B lines being *relatively* strong at low temperature.

Class III lines do not extend as far into the flame as those of Classes I B and II, but strengthen more rapidly toward the core. This condition becomes more pronounced for Classes IV and V, strong lines of the latter being very wide in the core and showing little extension into the flame. Good examples are $\lambda\lambda$ 5383.578, 5415.416, and others in that region.

Taken as a whole, it is found that an iron-arc spectrum produced by a plane grating in this way shows that the lines divide into classes according to their rate of growth in intensity as we pass from flame to core, in much the same way as they have been classified as to their rate of strengthening at various furnace temperatures. This agreement is only qualitative. There are many differences in detail for lines other than those of Class I A, and only the furnace is available if the spectrum resulting from a measured temperature is desired. However, the furnace results indicate that the changes in relative intensity of lines observed in passing from the outer vapors to the core of the arc are due largely to temperature differences.

If the melting and boiling points of iron are taken as 1500° C and 2450° C respectively, it is evident from the furnace results that iron vapor can be made to radiate much below the boiling-point. Since the highest furnace temperature is above the boiling-point of iron, the arc should give a spectrum similar to that of the furnace if the metal were simply boiling in the arc. We find, however, that to produce the arc spectrum would require the equivalent of a much higher temperature than is given by the furnace. Experimental evidence is lacking as to the exact nature of this difference between furnace and arc conditions, but it would seem that it is to be attributed mainly to the high electronic speeds given by the arc discharge.

Another point of interest is the fact that there appears to be little reason to ascribe the high intensity of Class I B and Class II lines in the flame of the arc to chemical action, especially to the increased oxidation to be expected in the flame vapors. In the furnace such chemical action as there is may be expected to increase with the temperature, and it is the low-temperature spectrum, presumably with minimum chemical action, which resembles most closely that given by the outer vapors of the arc. In fact, the material at hand indicates that relative changes in the spectrum do not result in any large degree from increase of oxidation. In the recent investigation of pressure effects[1] a set of furnace photographs was made for the blue and green-yellow regions of iron at atmospheric pressure and in compressed air up to 24 atmospheres. The brightness of the lines greatly increased, the radiation becoming stronger from end to end of the tube, as was evidenced by the general widening and the larger number of reversals; but no selective action, such as the bringing-out of some lines and the suppression of others, was to be seen, the nearest approach to the latter effect being for some high-temperature lines which did not reverse but were rendered very broad and hazy by pressure, so that unless the plates were strongly exposed such lines appeared greatly weakened. At atmospheric pressure, the spectrum is so closely similar to that in a partial vacuum, as regards relative intensity of lines, that the probability of oxidation playing an important part in the modification of a line spectrum, aside from general increase of intensity, seems very small.

COMPARISON WITH THE SPARK SPECTRUM

The evidence offered by the furnace is in agreement with the general phenomena of the arc and spark to the effect that the lines which are stronger in the spark than in the arc require a very high temperature or other abnormally violent excitation to bring them out. With one exception, all of the enhanced lines of iron listed by Lockyer[2] are entirely lacking in the furnace spectra. Only λ 3935.965 appears at high temperature, and this may be a barium line agreeing closely in wave-length which would be expected to show in the furnace. Most of the enhanced lines of iron are very faint in the arc, but the condition as to the weakness or absence of such lines in the furnace spectrum holds for other elements such as titanium, many of whose enhanced lines are strong in the arc.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 60; *Astrophysical Journal*, **35**, 183, 1912.

[2] "Tables of Wave-Lengths of Enhanced Lines," Solar Physics Committee, 1906.

A comparison with iron spark spectra made in this laboratory shows that the lines of Class I A, while present in the condensed spark, are produced with somewhat greater difficulty than in the arc, as would be expected from the general relations of arc and spark spectra. The connection of temperature changes in line intensities with those resulting from the use of self-induction with the spark will be made the subject of a later study.

COMPARISON WITH THE FLAME SPECTRUM

The investigations of Hemsalech and de Watteville have furnished material sufficient to establish the general character of flame spectra in reference to that of the furnace, though complete lists of lines for some of the flames have not been published. The flame lines given by de Watteville[1] as occurring in the outer vapors and those appearing at the boundary of the cone of a special air-coalgas flame correspond closely to the furnace spectra at low and medium temperatures respectively. The flame spectrum obtained by de Watteville extends farther into the ultra-violet than I have been able to photograph with the furnace, but his use of a quartz prism spectrograph for the flame may largely account for this, as comparisons of the extension into the ultra-violet are valid only when the same optical system is used. The possible absorption of short waves by the furnace vapors previously referred to may also affect this comparison with the flame. The list of flame lines does not include those which I have placed in Class I A for the furnace, with the exception of λ 4489.911. This would be remarkable were it not that de Watteville clearly omitted lines of this character which were relatively weak in the self-induction spark used by him for identification of the iron lines.

In an improved form of apparatus in which the iron vapor was generated by an arc in a closed chamber and then mixed with the gas which passed to the flame, Hemsalech and de Watteville[2]

[1] *Philosophical Transactions*, A, **204**, 139, 1904.

[2] *Comptes Rendus*, **146**, 859, 1908.

observed that an air-coalgas flame gave next to the cone a supplementary spectrum which did not appear in the hotter flames produced by combinations of oxygen with coalgas, air with hydrogen, and oxygen with hydrogen when used in the same apparatus. In a later paper[1] they noted that this "supplementary spectrum" contained a large number of lines in the ultra-violet which are given most strongly near the poles of the iron arc, many of them being relatively stronger in the spark than in the arc. These lines extend from λ 2374 to λ 3936.

Some of these "polar" lines appear in the high temperature furnace, but most of them are below λ 2700, in which region the furnace gives only the stronger arc lines. Recently the source named by the writer the "tube-arc" has been operated. The furnace tube is allowed to burn through with a high vaporization of carbon and the arc thus formed around the periphery has been shown[2] in the case of titanium, to give the enhanced lines strongly predominating. The tube-arc spectrum of iron reaches a shorter wave-length than the furnace spectrum, lines as far as λ 2327 having been photographed. Most of the polar lines noted by Hemsalech and de Watteville in the flame spectrum occur in the tube-arc, but I have not as yet been able to identify with certainty any of the enhanced lines of iron in the visible region. It thus appears that the polar lines in the ultra-violet do not require as strong excitation as do the enhanced lines of the visible spectrum, which is borne out by the fact that the former class of lines appear through the central region of the arc, though strongest close to the poles.

As to why the supplementary spectrum containing the polar lines did not appear in the hotter flames, I would venture to suggest that the condition noted by Hemsalech and de Watteville in a later paper[3] may furnish the explanation, namely, that in the more intense flames the strong current of gas carries the particles of iron vapor through the region of highest temperature too rapidly for the temperature to exert its full effect, while the more quiet conditions of the Bunsen flame may permit such temperature as exists to be fully felt. In other words, iron vapor introduced into the oxyhydrogen flame by this method may not be heated to the same degree as a solid body would be on which the flame is allowed to play.

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[1] *Comptes Rendus*, **146**, 1389, 1908.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 65; *Astrophysical Journal*, **37**, 119, 1913.

[3] *Comptes Rendus*, **150**, 329, 1910.

The oxyhydrogen flame spectrum of iron, of which 118 lines from λ 2483 to λ 5372 are given by Hemsalech and de Watteville,[1] must be classed as a low-temperature spectrum. Without exception, the lines in the visible portion belong in Class I B or Class II, whose strength at low temperature is characteristic. Many other lines should have appeared if the effective temperature of this flame had been as high as that for the medium-temperature furnace spectrum of Table I.

A study by the same authors[2] of the iron spectrum given by the oxyacetylene flame showed that in addition to the lines of the oxyhydrogen flame a set of lines occurs which are characteristic of the cone of the Bunsen flame, though not so strong as in the latter. The furnace spectrum shows that nearly all of these lines are in either Class III or Class II. If in the latter class, they show a rapid increase from low to medium furnace temperature. The strong Class III lines near λ 4900 are given in this set. This serves to place the oxyacetylene flame as corresponding to the furnace at the lower limit of the medium temperature. A conclusion equivalent to this was reached by Hemsalech and de Watteville by a comparison with the furnace results then at their disposal.

The several flames may thus be placed in the following order of their effective temperatures in producing radiation from iron vapor, the temperatures given being those read for the furnace when it gives in the visible region a spectrum similar in the lines present and in general relative intensities to that of the corresponding flame spectrum.

Flame	Furnace Temperature
Air-coalgas (outer vapors)	Below 1800° C.
Oxyhydrogen	About 1800°
Oxygen-coalgas	About 2000° to 2100°
Oxyacetylene	
Air-coalgas (cone)	About 2200°

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[1] *Ibid.*, **146**, 962, 1908.

[2] *Ibid.*, **150**, 329, 1910.

Judging from the furnace spectra, the flame temperature need not be higher than 2200° to produce the spectrum shown by the cone of the Bunsen flame and it may be appreciably lower. Furnace temperatures of 2400° and over not only gave a spectrum much richer in lines than is given by the Bunsen cone, but those lines which show a rapid growth with temperature are relatively much stronger. The lines classed as I A in the furnace spectra would be of value as an index to these low temperatures, but they were omitted by Hemsalech and de Watteville.

The difficulty remains to reconcile the above gradation of flames in the order of their spectroscopic efficiency with their relative temperatures as measured by melting-point tests. It seems at least plausible, however, that the explanation involves the mechanics of the flame gases, rather than the real thermal condition of each flame.

There is not enough material at hand to test definitely whether a certain flame yields the same spectrum as that of the furnace at equal temperature, though in the visible spectrum at least the evidence points that way. The list of flame lines by de Watteville[1] contains no lines between λ 3900 and λ 5600 which do not occur in the furnace. The medium-temperature furnace spectrum (2100°–2300°) contains more lines than the flame, the high-temperature furnace shows many more. Practically the same condition exists to about λ 2700; while farther in the ultra-violet, each source shows a number of lines apparently not given by the other. A further investigation of the extreme ultra-violet is required to show whether the use of different spectrographs and possibly the presence of foreign substances in furnace or flame (the identification of lines in this region often being uncertain) may be responsible in any large degree for this difference.

THE QUESTION OF TEMPERATURE RADIATION

The later work with the furnace has given no ground to modify the view expressed by the writer at the close of a paper[2] published over three years ago, in which it was pointed out that the furnace is not suited for crucial experiments as to the mechanism of the radiation, but that temperature is obviously the agent which sets this mechanism in operation and controls the observed variations in the furnace spectrum.

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[1] *Op. cit.*

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 35; *Astrophysical Journal*, **29**, 190, 1909.

The view appears to be gaining ground among spectroscopists that the emission of a line spectrum by temperature alone is possible and that quite probably it is given by the tube furnace, though definite proof of this cannot be claimed to have been offered. Opinions along this line have been clearly expressed in recent writings by Kayser[1] and by Schuster.[2] The vital question is whether a part of the translatory energy of the molecules due to heat can be changed to the "internal energy" which gives the emission of light. In this paper I wish to draw attention to several characteristics of furnace phenomena which bear more or less directly on the general problem.

1. There is unquestionably strong ionization from the carbon tube at the temperatures employed. Recent experiments by Harker have shown this to be the case at atmospheric pressure, while its existence at low pressure is well known.

2. Chemical reactions take place which are probably mainly of two kinds—combination with oxygen, the total exclusion of which is all but impossible even with the vacuum furnace, and the formation of iron carbide. The residue of iron is always found sticking fast to the interior of the tube and appears to eat into the graphite, this being perhaps in part due to the porosity of the latter.

3. The furnace radiation does not depend upon the existence of a potential difference. When the current is broken, the high-temperature lines gradually disappear, while some of the low-temperature iron lines have been observed 5 minutes, and the D lines of sodium 16 minutes after breaking the current. There is every reason to believe that if the tube could be as efficiently heated by a flame or other non-electrical source of heat, the radiation from the inclosed vapors would be the same as observed in these experiments.

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[1] *Zeitschrift für wissenschaftliche Photographie*, **8**, 151, 1910.

[2] Article "Spectroscopy," *Encyclopaedia Britannica*, 11th ed.

4. The increased oxidation due to the presence of air at, or much above, atmospheric pressure appears to have no distinct effect upon the spectrum for a given temperature aside from a general widening of the lines.

5. Many experiments have shown that when the furnace tube is obstructed by a plug or other mass of solid matter so as to approach black-body conditions, the weaker lines are entirely concealed by the continuous spectrum and the stronger lines thrown into absorption, indicating that the black-body radiation is stronger than that of the metallic vapor for any given wave-length.

SUMMARY

The ground covered in this investigation may be summarized as follows:

1. The relative intensities of iron lines in the visible spectrum have been given for three furnace temperatures and for the arc, with a division into six classes based on the temperature at which a line appears in the furnace and its rate of growth with increase of temperature.

2. The changes in relative intensities of lines observed in passing from the furnace to the arc may in general be accounted for by a difference in conditions equivalent to a large temperature difference, though one class of furnace lines presents difficulties in establishing a clear relation of this kind.

3. The red end of the iron spectrum appears to require high temperature for its production as compared to the blue region, and the distribution of lines through the visible spectrum bears little resemblance to the intensity gradation observed for the spectrum of an incandescent solid.

4. A preliminary examination of the ultra-violet showed this region to be very rich in lines given by the furnace. The extension of the line spectrum toward shorter wave-length with increase of temperature was observed, it being found that lower limits were reached for a given temperature by the spectrum of an incandescent solid.

5. A list is given of pairs of lines whose members belong in different classes as regard response to temperature changes and

may be used in estimating the relative temperatures of light sources.

6. The increase in intensity of lines from the outer vapors into the core of an iron arc was found usually to resemble the rate of growth shown by the same lines with rising furnace temperature. This renders it unlikely that chemical reactions in the outer vapors affect the relative intensity of arc lines in any large degree.

7. The enhanced lines of iron in the visible region have not been observed in the furnace spectrum.

8. A comparison with published data on flame spectra has shown how the various flames are probably related as to effective temperatures in producing radiation. Except perhaps in the ultra-violet, furnace spectra at low and medium temperatures are found to be very similar to those of the several flames.

9. While presenting no definite proof that temperature radiation in a strict sense takes place, the position of temperature as the exciting and regulating agent in furnace phenomena seems to be clear.

Miss Sheldon of the Computing Division has rendered frequent assistance in this work, especially in the examination of plates for the ultra-violet spectrum.

Mount Wilson Solar Observatory
October 17, 1912

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THE SPECTRA OF SPIRAL NEBULAE AND GLOBULAR STAR CLUSTERS

THIRD PAPER

By E. A. FATH

Since the writing of the second paper[1] a number of additional spectrograms have been obtained with the Mount Wilson 60-inch reflector.

The spectrograph used was the same as before except for the last plate, taken in May 1912. For this a new spectrograph, mounted directly in the axis of the telescope, was available. The collimator lens of the new instrument has an effective aperture of 3.6 inches and a focal length of 18 inches. The prism is of UV flint, has an angle of 30 degrees, and will include the full beam. The camera lens has an aperture of 4 inches and a focal length of 8 inches. It is a special lens of portrait type made for the Yerkes Observatory and loaned for this investigation. For this courtesy the writer desires to express his great appreciation. There was no opportunity, at the time, to test the relative speed of the two spectrographs but it seems very probable that the new one has about twice the speed of the other. Lumière "Sigma" plates were used throughout. The method of measurement of the spectrograms was the same as that employed before.

SPIRAL NEBULAE

N.G.C.	Dates of Exposure	Total Exposure
1023.......	1910 Nov. 29, 30, Dec. 1, 2	$20^{h}40^{m}$
1023.......	1911 Oct. 19, 20, 21, 22	38 14
3031.......	Jan. 4, 5, 6	22 39
4594.......	Mar. 29, 30, 31, Apr. 1	17 8
4736.......	May 2	7 40
4826.......	1912 Feb. 10, 11, 12	16 15
5194.......	1911 Apr. 28, 29, 30, May 1	29 20
7331.......	1910 Aug. 27, 28	12 18

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 49; *Astrophysical Journal*, **33**, 58, 1911.

Owing to a discontinuation of the observations, a description is given of a number of spectrograms which are underexposed, although the information to be derived from such plates is very meager.

As before we shall consider the two classes of objects separately.

N.G.C. 1023.—Absorption lines corresponding to F, 436 $\mu\mu$, G, H, and K are present. The line at 436 $\mu\mu$ may be H_γ, but as it is about 2 $\mu\mu$ to the red of the H_γ position this identification does not appear probable. The grain of the plate having the longer exposure is exceedingly troublesome. The spectrum is very narrow in each case. The general appearance of the spectrum is similar to that of the sun.

N.G.C. 3031.—This is a very good plate. In appearance it exactly resembles the spectrum of a K-type star. There are absorption lines at F, 454, 448, 440 $\mu\mu$, G, groups at 419 and 406 $\mu\mu$, H, and K.

N.G.C. 4594.—This negative is very weak. It is not safe to say more than that the color-curve indicates a spectrum of approximately solar type.

N.G.C. 4736.—As stated in the second paper, there is a difference between the Mount Hamilton[1] and the Mount Wilson plates obtained by the writer, the former being apparently somewhat out of focus while the latter is in good focus and shows absorption lines like the sun. Another plate was taken to check the two preceding. The definition of the third plate is not quite as good as in the first Mount Wilson plate and shows an appearance somewhat like the Mount Hamilton plate, namely, a broadening and slight intensification immediately to the red of H, at 406 $\mu\mu$. Otherwise it agrees fully with the first Mount Wilson plate in showing the prominent solar lines. The latter plate, upon careful examination, also shows the effect at 406 $\mu\mu$ but by no means so prominently as the last. In order to bring out this brighter band it therefore seems necessary to suppress the absorption lines.

N.G.C. 4826.—This plate is very weak. The color-curve is similar to that of a solar-type star.

N.G.C. 5194.—The spectrum is weak in spite of an exposure of nearly 30 hours. The large mirror was in very poor condition at the time this exposure was made. This doubtless was the cause of the faintness of the spectrum. The color-curve is similar to that of a K-type star. Lines at G and H are certainly present.

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[1] *Lick Observatory Bulletin*, No. 149.

N.G.C. 7331.—The plate is underexposed. Lines corresponding to F, G, and H are found. Two other absorption lines are present, one on either side of G, but their position cannot be determined with any accuracy because of the faintness and narrowness of the spectrum. This plate agrees with the Mount Hamilton plate obtained in 1908 which shows lines at G and H.

In the last four years the writer has investigated the spectra of eleven nebulae, *N.G.C.* 224, 650–1, 1023, 1068, 3031, 4594, 4725, 4736, 4826, 5194, and 7331, of which all but 650–1 are certainly spiral. For the most part the spectra are either G- or K-types. In the case of some of the nebulae the spectrum obtained came largely from the nucleus, but this is certainly not the case with the great *Andromeda* nebulae in which a spectrum of solar type was obtained over a strip five minutes of arc in length.

N.G.C. 1068 and 4736.—These are peculiar. The first shows bright nebular lines together with dark lines, although the type of absorption spectrum is not evident. In the case of the second there is increased radiation in the vicinity of 406 $\mu\mu$ near the position of one of the bright lines in some of the Wolf-Rayet stars. These two cases are the only ones in the series of plates secured by the writer at Mount Hamilton and at Mount Wilson which give definite evidence of what may be termed "gaseous" radiation. In a paper[1] published when the present one was practically completed, Professor Max Wolf reports finding emission lines in a number of spiral nebulae, many of which correspond to emission lines in Wolf-Rayet stars. Though the writer's plates show definite emission lines in but two cases, the two series cannot be considered contradictory. Wolf's plates were on about double the scale (spectra 6 mm in length) of those here described, and apparently a finer-grained plate was used.

N.G.C. 5904.—The following absorption lines are present: F, H_γ, G, H, K, and a band at 419 $\mu\mu$ which may possibly be double.

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[1] *Sitzungsber. Heidelberger Akad. d. Wiss.*, Abt. A, 1912, No. 15.

The appearance is practically that of a solar spectrum except that H_γ is more prominent here than in the sun.

GLOBULAR CLUSTERS

N.G.C.	Dates of Exposure	Total Exposure
5904…….	1911 May 3, 4, 5	16^h17^m
6093…….	June 1, 2, 3	15 40
6205…….	1912 May 21, 22, 23	15 35
6254…….	1911 May 30, 31	13 05

N.G.C. 6093.—This spectrum is of good density. Absorption lines corresponding to solar F, G, H_δ, H, and K are present. The line corresponding to H_δ is stronger than in the sun. Aside from this the spectrum resembles the solar type. H_γ may be present, for G looks broader than normal.

N.G.C. 6205.—This exposure was made with the second spectrograph as noted above. The exposure of 15^h35^m therefore corresponds to about 31^h when compared with the others. It is the first spectrogram of satisfactory density of this cluster which I have obtained and seems to explain the discrepancy between the first plate obtained at the Lick Observatory[1] and the first Mount Wilson plate.[2] The Lick plate, although faint, indicated stars of various spectral types. These could be picked out because the guiding was such that the cluster was kept quite closely in one position with respect to the slit. The cluster being comparatively coarse, the spectra of but few stars were obtained. On the other hand, for the first Mount Wilson plate, the guiding was such as to allow the cluster to drift slightly in both α and δ. A more nearly average type of spectrum was thus obtained and the F-type was indicated. The plate, however, was not of satisfactory density, so another was taken. In this case a special effort was made to obtain an average spectrum by making the image of the cluster move about over the slit. The spectrum obtained shows absorption lines at H_β, H_γ, G, H_δ, H, and K and a band at 420 $\mu\mu$. H_γ and G appear as a close double line while H and K are not fully separated. The plate thus indicates either a type of spectrum between F and G, or stars ranging from the one type to the other. If we take the latter, we have approximate agreement among the three plates. A re-examination of the first Mount Wilson plate brought out the fact that the line called H_γ is broader than the others and therefore favors the possibility of its being double as shown in the last plate.

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[1] *Lick Observatory Bulletin*, No. 149.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 49; *Astrophysical Journal*, **33**, 58, 1911.

N.G.C. 6254.—This is a comparatively coarse cluster and the spectrum of but one star can certainly be identified. It is of solar type and shows the F, G, H, and K lines. The spectrum of another star is on the plate but it is much fainter than the former, which it appears to resemble. The lines F, H, and K are probably present. G may also be present but the very slight width of the spectrum and the troublesome grain of the plate make this very uncertain.

The four clusters described above agree in showing the solar line G as well as lines of hydrogen and calcium. We thus have three possibilities—the clusters consist of: (1) stars of F and G types, (2) stars of a type intermediate between F and G, possibly F8 in the Harvard classification; (3) a combination of 1 and 2. The latter hypothesis seems most probable.

After the presence of the G line had been recognized in these four cases the spectrograms of the clusters discussed in the second paper were carefully examined again. With the exception of the plate of *N.G.C.* 6205, mentioned above, they gave no evidence of being composed of other than F-type stars.

The number of globular clusters investigated thus numbers twelve, approximately 11 per cent of those of appreciable size and brightness. As stated in the second paper, only the brighter stars of the clusters had any effect on the photographic plate. The result obtained thus far may be stated as follows: *As a whole the brighter stars of the globular clusters investigated have spectra ranging only from the F- to the G-type.* The clusters observed are nearly all that can readily be reached in latitude 34° north and in which the brighter group of stars are fairly condensed and of sufficient brightness to be observed in a reasonable time. Unfortunately these do not include the large group of clusters near 18 hours and south of −20°. It would be of great interest to know if these, too, show the same small range of spectral type as the northern clusters, and it is hoped that some southern observatory may undertake to answer this question.

Smith Observatory
Beloit, Wis.
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THE *ALGOL* VARIABLE *RR DRACONIS*
SECOND PAPER

By FREDERICK H. SEARES

The comparison of the photographic results for *RR Draconis* presented in the first paper[1] with the incomplete visual light-curve indicated that the photographic variation is greater than the visual. An examination of the relative dimensions and light-intensities of the two objects composing the system made it practically certain that the difference must be real. This result has since been confirmed by photographs during the minimum of September 10, 1912, made alternately on ordinary and isochromatic plates, the latter being used with a yellow filter. The present paper contains an account of these later observations.

The plates used were Seed "Gilt Edge 27" and Cramer "Instantaneous Isochromatic." The filter is one prepared for the determination of visual magnitudes, and when used in connection with the Cramer plate, the curve of color sensitiveness for spectral types not too far advanced appears to agree satisfactorily with that of the eye. The results derived with this combination will, in what follows, be referred to as photovisual[2] magnitudes.

During the period of variation on September 10, 18 plates, divided equally between the Seed "27" and the Cramer "Iso," were made with the full aperture of the 60-inch reflector. Five one-minute exposures were made on each of the Seed plates, while four exposures of three minutes each were given to all the Cramer plates excepting the last, for which the exposures were two minutes. The total number of exposures is therefore 81. They cover the minimum and parts of both branches of the curve, and extend over an interval of $5^h 27^m$. The atmospheric conditions were satisfactory throughout. The transparency was high, and the steadiness ranged from 3 to 4 on a scale of 10. Further details are given in Tables IX–XI, but before proceeding to their discussion it is necessary to consider the magnitude scale of the comparison stars.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 64; *Astrophysical Journal*, **36**, 368, 1912.

[2] The increasing importance of visual magnitudes determined by photographic methods suggests the desirability of a special designation for results so derived. Though etymologically unsatisfactory, the term *photovisual* is suggested as a convenient notation, the term *visual* being reserved for the indication of results to which hitherto it has generally been applied.

The relative photographic magnitudes of the comparison stars have already been well determined. Referred to an arbitrary zero point, they are shown in the second column of Table IV of the first paper and of Table III below. The results of a provisional determination of the zero point from a plate of duplicate exposure on the field of the variable and on the Pole are given in the last column of Table IV of the first paper. As a control upon this comparison two further photographs of duplicate exposure have since been made on Seed "27" plates. In addition, a series of photographs on Cramer "Iso" plates has been made for the derivation of the photovisual scale used for the reduction of the isochromatic plates exposed during the minimum on September 10. A list of the additional photographs made for scale determinations is given in Table I. Those on "Iso" plates include exposures with the various apertures used for the determination of the relative photovisual magnitudes, and also duplicate exposures on the field of the variable and on the Pole, the latter serving to fix the zero point of the photovisual scale.

Turning first to the revision of the zero point of the photographic scale, we have available plates 902 and 903. The images of the comparison stars for the variable and the Polar Sequence stars shown on these plates were measured with the photometric scale in the usual manner. These exposures were made with a 32-inch diaphragm, and as the distances of the stars from the axis were moderate, we may regard the field as free from aberration. The mean scale readings, uncorrected for distance error, are therefore used for the reduction. These are given in Table II. The numbers and magnitudes of the polar stars are from *Harvard Circular*, No. 170, with the exception of (350) and (362), for which the numbers refer to *Harvard Annals*, **48**, as these objects are not included in the Polar Sequence. Their magnitudes are from an investigation of the Polar Sequence not yet completed, but as the results for this part of the scale are in close agreement with those of Pickering, they may be used for the present purpose.

TABLE I

PLATES FOR MAGNITUDE SCALE OF COMPARISON STARS

Plate	Date	G.M.T.	No. Exp.	Exp. Time	Aperture	Region	Seeing
P 845, "Iso"..	1912 Sept. 15	19^h22^m–19^h33^m	4	3^m	60, 32	Variable	3
846, "Iso"..	15	19 40 –20 0	6	3	60, 32, 14	Variable	3
847, "Iso"..	15	20 5 –20 23	3	3	60	Var., Pole	3–4
856, "Iso"..	16	18 17 –18 32	4	4	60, 32	Variable	5
857, "Iso"..	16	18 41 –19 0	4	4	60, 32	Variable	5
858, "Iso"..	16	19 7 –19 23	3	3	60	Var., Pole	5
900, "Iso"..	Oct. 7	15 40 –16 24	3	10	32	Var., Pole	4
901, "Iso"..	7	16 37 –17 20	3	10	32	Var., Pole	3
902, "27"...	7	17 31 –17 57	3	4	32	Var., Pole	3
903, "27"...	7	18 0 –18 22	3	4	32	Var., Pole	2–3

TABLE II

COMPARISON WITH THE POLE—PHOTOGRAPHIC RESULTS

POLAR SEQUENCE				VARIABLE AND COMPARISON STARS		
H.C. 170		Scale Reading		Star	Scale Reading	
Star	Mag.	902	903		902	903
14	10.52	9.0	8.3	*v*	6.6	6.5
7*r*	10.57	9.4	8.6	1	6.9	6.8
(350)	10.63	9.5	8.8	2	13.1	13.8
5*s*	10.68	9.5	8.9	3	13.7	14.0
16	11.26	11.6	11.5	4	13.7	14.4
19	12.28	14.6	15.6	5	14.5	14.4
7*s*	12.31	14.5	14.7	6	15.1	15.2
20	12.59	14.8	16.4	7	14.8	15.0
(362)	12.78	16.2	17.8	8	15.5	16.5
11*r*	12.83	17.2	18.0	9	16.2	...
23	13.20	18.0	....	10	17.4	16.8
12*r*	13.34	18.5	....	11	17.6	....
24	13.50	18.5	....	..	....	....

The scale readings for the polar stars were plotted against the magnitudes in the second column of Table II, and from the resulting curves were interpolated the magnitudes of the comparison stars and the variable. These results require a correction for extinction.

The zenith distances for the variable for the mean times of exposure of plates 902 and 903 were respectively 48°7 and 52°5.

The corrections are therefore +0.10 and +0.05 mag. The corrected values of the interpolated magnitudes are given in fourth and fifth columns of Table III. The corresponding quantities for plate 792, derived by adding the correction for extinction to the results in the eighth column of Table IV of the former paper, are also given in Table III. The magnitudes of the variable and of star No. 1 from plates 902 and 903 are unreliable, as they represent an extrapolation of the magnitude-curve defined by the Polar Sequence stars. On this account they are not used in the derivation of the reduction constant, though they may be accepted for a further determination of the relative brightness of the variable and star No. 1. The value previously found was *v*—No. 1 = —0.15 mag. with weight 6. From plates 902 and 903 we derive —0.10 mag. with weight 2. The mean is —0.14 mag. On this account the provisional magnitude of the variable in Table III is 0.76 instead of 0.75, as previously given.

TABLE III

Photographic Magnitudes of Comparison Stars

Star	Prov. Mag.	Interpolated Mag.			Reduction to P.S.			Adopted Mag.	Mag. from P.S.	Diff.
		792	902	903	792	902	903			
v...	0.76	.....	(9.78)	(9.99)	....	(9.02)	(9.23)	9.64	(9.88)	(−24)
1...	0.90	.....	(9.89)	(10.08)	....	(8.99)	(9.18)	9.78	(9.98)	(−20)
2...	3.03	12.07	11.96	12.01	9.04	8.93	8.98	11.91	12.01	−10
3...	3.12	12.27	12.13	12.05	9.15	9.01	8.93	12.00	12.15	−15
4...	3.23	12.18	12.13	12.15	8.95	8.90	8.92	12.11	12.15	− 4
5...	3.40	12.40	12.40	12.15	9.00	9.00	8.75	12.28	12.32	− 4
6...	3.68	12.73	12.58	12.35	9.05	8.90	8.67	12.56	12.55	+ 1
7...	3.70	12.58	12.49	12.32	8.88	8.79	8.62	12.58	12.46	+12
8...	4.02	12.90	12.69	12.65	8.88	8.67	8.63	12.90	12.75	+15
9...	4.03	12.96	12.87	.....	8.93	8.84	....	12.91	12.92	− 1
10...	4.06	12.96	13.19	12.72	8.90	9.13	8.66	12.94	12.96	− 2
11...	4.28	13.00	13.23	.....	8.72	8.95	....	13.16	13.12	+ 4
12...	4.58	.....	.....	.....	....	....	....	13.46	.....	....
13...	4.80	.....	.....	.....	....	....	....	13.68	.....	....
14...	4.89	.....	.....	.....	....	....	....	13.77	.....	....
Means..........................					8.95	8.91	8.77			
Adopted mean reduction to Polar Sequence.......................						8.88				

The comparison of the interpolated magnitudes with the provisional results in the second column of Table III gives the values of the reduction constants shown in columns six, seven, and eight. The respective means of 8.95, 8.91, and 8.77 mags. are in satisfactory agreement, and yield as a mean constant for the reduction of the provisional magnitudes to the zero point of the Polar Sequence, 8.88 mags. The final values for the normal brightness of the variable and for the magnitudes of the comparison stars are in column nine of Table III. As a result of the revision, the magnitude of the variable has been decreased by 0.06, the comparison stars by 0.07.

It will be noted that the scale of the adopted magnitudes has been independently derived, and, excepting the zero point, is in nowise based on that of the Polar Sequence. It is of interest, however, to compare the two scales, which is easily done by forming the mean of the interpolated magnitudes for each star. The results are in the column following the adopted magnitudes in Table III. The differences in the last column, with the exception of the first two which are without significance, are all small. There is a suggestion of a small systematic difference, but the interval covered is too short to afford a reliable indication.

Proceeding now to a consideration of the photovisual scale, we have available for the determination the diaphragm plates 845, 846, 856, and 857, all of which were made during normal brightness of the variable. The scale readings for these appear in Table IV. The values in parentheses for star No. 1 are those actually observed, corrected for distance error by means of the average curve ordinarily used for the full aperture of the 60-inch reflector. But, as pointed out in the former paper, these corrections are uncertain in the case of bright stars at any considerable distance from the axis, on account of the large influence of even comparatively small deformations of the mirror. Star No. 1 is of this character, and to avoid the difficulty, the following procedure was followed: The variable during normal light is very nearly of the same brightness as star No. 1 but is situated at the center of the plate. If, therefore, the value of the difference in brightness of the two objects can be independently derived, it will be possible to apply this difference to the scale readings for the variable and derive for star No. 1 values which will be more reliable than those observed. The required differences may be found from the exposures made with the 32- and 14-inch diaphragms, the results for which are also entered in Table IV. Two additional values are also given by the polar comparison plates, 900 and 901, listed in Table VI, both of which were made with the 32-inch diaphragm. Since the difference is very small, amounting to only 0.04 or 0.05 mag., we may disregard the small fluctuations in the value of the scale interval from plate to plate and for different parts of the scale. We thus find No. $1-v=+0.14$ scale interval, which, added to the 60-inch exposure values for the variable in the first line of Table IV, gives the required values for star No. 1. These were used in the determination of the magnitude scale instead of those directly observed.

TABLE IV

Mean Readings for Photovisual Scale Plates

Star	845		846			856		857	
	S_{60}	S_{32}	S_{60}	S_{32}	S_{14}	S_{60}	S_{32}	S_{60}	S_{32}
v	6.4	13.6	6.2	13.6	16.4	8.5	13.5	7.5	12.9
1	(7.5) 6.5	13.7	(7.4) 6.3	13.6	17.3	(7.8) 8.6	13.6	(7.5) 7.6	13.2 ....
2	13.5	....	13.7	....	....	13.7	....	13.0	....
3	14.5	....	14.2	....	....	14.4	....	13.7	....
4	14.4	....	14.0	....	....	14.1	....	13.6	....
5	11.9	....	11.9	....	....	12.5	....	11.8	....
6	....	....	16.8	....	....	16.1	....	15.3	....
7	14.6	....	15.1	....	....	14.3	....	14.3	....
8	16.7	....	16.8	....	....	15.6	....	15.0	....
9	16.4	....	16.3	....	....	16.2	....	15.3	....
10	....	....	....	....	....	16.5	....	15.7	....

The data in Table IV permit of five separate determinations of the scale of photovisual magnitudes. The exposures were too short for those with the diaphragms to show images for any of the stars excepting the variable and No. 1, and, as these are of the same brightness, we have, in effect, to assume that the photometric scale with which the images were measured is a uniform scale of magnitudes whose constant is to be determined for each plate. Fortunately this is sensibly the case. The resulting mean magnitudes referred to an arbitrary zero point, and the deviations in hundredths of a magnitude, for each determination of the scale are in Table V. The average deviation, including the effect of relative scale error over a range of three magnitudes, is ±0.045 mag.

TABLE V

PROVISIONAL PHOTOVISUAL MAGNITUDES

Star	Provisional Mag.	Residuals				
		845	846		856	857
		60–32	60–32	60–14	60–32	60–32
v	1.73	−5	−4	+8	+2	0
1	1.80	−2	0	0	+5	−2
2	3.76	+3	−3	−4	0	+2
3	3.98	−2	+6	+4	−6	−1
4	3.92	−5	+5	+4	0	−4
5	3.29	+1	−1	0	0	−1
6	4.65	...	+2	−2	−7	+8
7	4.12	+9	−5	−7	+12	−9
8	4.58	−3	−5	−9	+6	+11
9	4.58	+5	+9	+5	−18	+1
10	4.80	...	...	...	−8	+8
Average deviation	....	±0.039	±0.040	±0.043	±0.058	±0.043

The zero point of the photovisual scale was derived from the polar comparison plates 847, 858, 900, and 901. The arrangement of Table VI, which contains the scale readings, is similar to that of Table II. It is to be noted, however, that the visual magnitudes of the Polar Sequence stars from *Harvard Circular*, No. 170, are here used instead of the photographic. Precisely the same method has been followed in deriving the reductions to the Pole as was used for the photographic magnitudes. The zenith distances of the variable and the corresponding corrections for extinction were:

	Plate			
	847	858	900	901
Zenith Distance	54°.7	48°.2	37°.5	43°.8
Extinction	+0.02	+0.10	+0.19	+0.15

The magnitudes interpolated from the curves defined by the data for the Polar Sequence stars and corrected for extinction are in columns three to six of Table VII. The provisional magnitudes in the second column are as given in Table V, except that the value for the variable has been revised to include the results from plates 900 and 901, which, having been made with the 32-inch diaphragm, are available for the determination of the relative brightness of the variable and star No. 1. The arrangement of Table VII and the

TABLE VI

COMPARISON WITH THE POLE—PHOTOVISUAL RESULTS

Polar Sequence						Variable and Comparison Stars				
H.C. 170		Scale Reading				No.	Scale Reading			
No.	Mag.	847	858	900	901		847	858	900	901
10.......	8.94	....	....	8.7	8.8	*v*	6.3	8.3	12.0	11.8
7*r*......	9.84	....	....	11.6	11.8	1	7.6	8.0	11.7	11.7
5*s*......	9.86	7.5	7.3	11.7	11.8	2	14.2	14.0	16.0	16.1
14.......	10.44	....	....	13.2	13.3	3	14.8	14.5	17.4	17.3
15.......	10.78	....	....	13.7	13.8	4	14.9	14.4	16.7	17.1
16.......	11.07	....	....	14.5	15.0	5	12.6	12.7	14.6	14.7
19.......	12.22	....	15.3	18.3	18.2	7	15.4	15.6	17.8	....
11*r*......	12.24	14.1	14.7	18.2	17.7	8	17.2	17.1	....	....
20.......	12.65	16.4	16.8	....	.....	9	17.4	16.7	....	....

TABLE VII

PHOTOVISUAL MAGNITUDES OF COMPARISON STARS

Star	Provisional Mag.	Interpolated Magnitude				Reduction to Polar Sequence				Adopted Mag.	Mag. from P.S.	Difference
		847	858	900	901	847	858	900	901			
v........	1.76	9.47	10.27	10.26	10.07	7.71	8.51	8.50	8.31	9.98	10.02	− 4
1........	1.80	9.92	10.17	10.15	10.03	8.12	8.37	8.35	8.23	10.02	10.07	− 5
2........	3.76	12.16	12.04	11.68	11.72	8.40	8.28	7.92	7.96	11.98	11.90	+ 8
3........	3.98	12.36	12.19	12.16	12.22	8.38	8.21	8.18	8.24	12.20	12.23	− 3
4........	3.92	12.39	12.16	11.91	12.15	8.47	8.24	7.99	8.23	12.14	12.15	− 1
5........	3.29	11.62	11.74	11.18	11.15	8.33	8.45	7.89	7.86	11.51	11.42	+ 9
6........	4.65	.....	.....	.....	.....	....	....	....	....	12.87	.....	....
7........	4.12	12.53	12.51	12.28	.....	8.41	8.39	8.16	....	12.34	12.44	−10
8........	4.58	12.96	12.88	.....	.....	8.38	8.30	....	....	12.80	12.92	−12
9........	4.58	13.00	12.80	.....	.....	8.42	8.22	....	....	12.80	12.90	−10
10........	4.80	.....	.....	.....	.....	....	....	....	....	13.02	.....	....
Means..........................						8.29	8.33	8.14	8.14			
Adopted mean reduction to Polar Sequence.........................						8.22						

method of reduction to the zero point of the Polar Sequence is the same as that for Table III. As before, the last column gives the difference between the adopted magnitudes resulting from the independent determination of the scale and the means of the interpolated magnitudes which are based upon the Harvard values for the Polar Sequence stars. With the exception of a small constant difference due to the particular distribution of the data used, the agreement between the Harvard visual scale and the photovisual results obtained with the "Iso" plate and yellow filter is satisfactory.

TABLE VIII

ADOPTED MAGNITUDES

Star	Photographic Mag.	Photovisual Mag.	Color Index	Spectrum	
				H. Mags.	Mt. W. Mags.
v...(Normal Brightness)	9.64	9.98	−0.34	B4	A2
1	9.78	10.02	−0.24	B6	A4
2	11.91	11.98	−0.07	B9	A8
3	12.00	12.20	−0.20	B6	A5
4	12.11	12.14	−0.03	A0	A9
5	12.28	11.51	+0.77	F8	G6
6	12.56	12.87	−0.31	B4	A2
7	12.58	12.34	+0.24	A6	F5
8	12.90	12.80	+0.10	A3	F1
9	12.91	12.80	+0.11	A3	F1
10	12.94	13.02	−0.08	B9	A8
11	13.16	.....	......	...	...
12	13.46	.....	......	...	...
13	13.68	.....	......	...	...
14	13.77	.....	......	...	...

In Table VIII are collected the final results for the normal brightness of the variable and for the various comparison stars. The fourth column contains the color index, and the fifth, the corresponding spectrum interpolated from the curve of Parkhurst.[1] The apparent preponderance of very early type spectra raises a question as to whether the two scales, if extended to stars of the sixth magnitude, would coincide for stars of the type A0. There is, of course, some uncertainty in the zero points of the adopted scales owing to the small number of comparisons with the Pole. The average deviation of the separate values of the reduction constants from their means are respectively 0.07 and 0.08 mag. One would not expect, therefore, a relative error greater than a tenth of a magnitude, assuming both the photographic and visual magnitudes used for the Polar Sequence stars to be correct. But an error even of this amount would not be sufficient to account for the deviation of the spectra from the normal distribution.

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[1] "Yerkes Actinometry," *Astrophysical Journal*, **36**, 217, 1912.

The results become more satisfactory, if, instead of the Harvard photographic magnitudes for the Polar Sequence stars, we use the values from an investigation with the 60-inch reflector for which preliminary results have recently been obtained. The agreement of the Mount Wilson scale with that of Harvard is excellent for the stars between the tenth and fifteenth magnitudes, but for the brighter stars there is a well-marked divergence amounting to about 7 per cent. If the two scales be brought into coincidence at the sixth magnitude in accordance with the international convention, it appears that the Mount Wilson magnitudes for the fainter stars are fainter than those of Harvard. The difference increases uniformly from the sixth to the tenth magnitude, but from there on is constant and equal to 0.37 mag. Since all of the Polar Sequence stars used above for the determination of the zero point of the photographic scale are fainter than the tenth magnitude (see Table II), the results in the second and fourth columns of Table VIII may be reduced to the Mount Wilson system by the simple addition of 0.37 mag. The spectra corresponding to this modification are given in the last column of Table VIII. It will be observed that the distribution is now normal, and, further, that the spectrum for the variable is now in sensible agreement with the Harvard value A5?.[1] The result is of interest, but not conclusive, for we have practically no reliable information as to the distribution of the spectra of the fainter stars; and, moreover, we are here dealing with only a small group of objects. But as the main purpose of the present discussion is the determination of the relative values of the photographic and the visual variation of *RR Draconis*, the uncertainty is of no immediate consequence.

[1] *Annals Harvard College Observatory*, **56**, 189.

The data relating to the observations during the period of variation are in Tables IX–XI. The scale readings have been corrected for distance error, and those for the variable have been reduced to the mean exposure by the method used for the first series. As before, there is no evidence of systematic difference between the first and last exposures on the same plate. The values of the brightness of the variable in the seventh column of Table XI were interpolated from the magnitude-curves formed with the adopted magnitudes of the comparison stars in Table VIII and the scale readings in Tables IX and X, the argument used being the scale reading in the sixth column of Table XI.

TABLE IX

Mean Scale Readings of Comparison Stars—Photographic Results

Star	813	815	817	819	821	823	825	827	829
1	5.0	5.8	5.2	4.6	6.3	6.3	5.6	5.6	5.4
2	12.5	12.0	....	10.7	12.0	11.5	11.6	11.9	11.6
3	12.4	12.2	....	11.4	12.4	12.1	11.9	11.8	11.8
4	12.5	12.4	12.1	11.6	12.8	12.2	12.2	12.0	12.0
5	12.8	12.7	12.1	11.5	12.4	12.1	12.2	12.0	12.1
6	13.5	13.0	12.3	12.3	13.5	13.3	12.7	12.6	12.8
7	13.3	12.9	12.4	12.3	13.3	13.0	12.6	12.5	12.5
8	13.6	13.4	13.1	12.9	14.0	13.5	13.3	13.2	13.4
9	13.7	13.4	13.2	13.2	14.3	13.9	13.3	13.4	13.5
10	13.7	13.7	13.2	13.8	14.1	13.9	13.5	13.5	13.7
11	14.1	13.5	13.1	13.8	14.0	14.0	13.8	13.6	14.1
12	14.9	14.3	14.1	14.6	14.7	14.6	14.5	14.3	14.8
13	15.5	15.3	15.1	15.4	15.6	15.2	14.9	15.0	15.7
14	15.6	15.5	15.3	15.8	15.8	15.9	15.5	15.6	16.2

TABLE X

Mean Scale Readings of Comparison Stars—Photovisual Results

Star	814	816	818	820	822	824	826	828	830
1	7.8	7.8	7.8	8.3	9.7	7.8	8.0	7.8	9.1
2	14.0	13.6	13.7	14.0	14.3	13.0	13.6	13.4	15.1
3	14.6	14.2	14.3	14.6	15.3	13.7	14.0	13.8	15.6
4	14.6	14.1	14.2	14.5	15.0	13.6	13.8	13.8	15.4
5	12.9	12.2	12.3	13.1	13.6	11.8	12.3	11.9	13.4
6	16.4	16.2	16.2	15.9	16.6	15.0	15.4	15.5	....
7	15.1	14.7	14.6	15.0	16.0	14.2	14.5	14.4	17.1
8	16.4	16.0	15.9	16.1	17.0	15.0	15.8	15.5	17.8
9	16.4	16.0	15.8	15.8	16.8	14.8	15.2	15.4	17.8
10	17.1	16.6	16.7	16.8	....	15.6	15.7	16.1	....

TABLE XI

MEAN SCALE READINGS AND MAGNITUDES OF *RR Draconis*

1912, September 10

PHOTOGRAPHIC RESULTS

Plate	Exposure	G.M.T.		Phase	*s*	Mag.	O−C
P 813......	1	$15^{h}20^{m}5$	$0^{d}639$	$-0^{d}107$	7.4	10.39	+ 4
	2	22.5	0.641	−0.105	7.3	10.36	0
	3	24.5	0.642	−0.104	7.5	10.42	+ 4
	4	26.5	0.644	−0.102	7.1	10.31	−12
	5	28.5	0.645	−0.101	7.8	10.50	+ 6
815......	1	16 5.5	0.671	−0.075	9.2	10.93	− 7
	2	7.5	0.672	−0.074	9.6	11.07	+ 5
	3	9.5	0.674	−0.072	9.7	11.11	+ 2
	4	11.5	0.675	−0.071	9.8	11.15	+ 3
	5	13.5	0.676	−0.070	10.2	11.30	+15
817......	1	16 47.5	0.699	−0.047	11.9	12.34	+ 7
	2	49.5	0.701	−0.045	11.8	12.29	−11
	3	51.5	0.702	−0.044	12.1	12.44	− 1
	4	53.5	0.703	−0.043	12.1	12.44	− 9
	5	55.5	0.705	−0.041	12.6	12.66	+ 2
819......	1	17 22.5	0.724	−0.022	14.8	13.52	+ 6
	2	24.5	0.725	−0.021	14.7	13.50	+ 4
	3	26.5	0.727	−0.019	14.8	13.52	+ 6
	4	28.5	0.728	−0.018	14.7	13.50	+ 4
	5	30.5	0.729	−0.017	14.8	13.52	+ 6
821......	1	18 2.5	0.752	+0.006	15.2	13.52	+ 6
	2	4.5	0.753	+0.007	15.1	13.47	+ 1
	3	6.5	0.755	+0.009	15.0	13.43	− 3
	4	8.5	0.756	+0.010	15.0	13.43	− 3
	5	10.5	0.757	+0.011	15.1	13.47	+ 1
823......	1	18 36.5	0.776	+0.030	14.8	13.49	+ 6
	2	38.5	0.777	+0.031	14.5	13.35	− 7
	3	40.5	0.778	+0.032	14.5	13.35	− 5
	4	42.5	0.780	+0.034	13.8	13.00	−20
	5	44.5	0.781	+0.035	14.2	13.19	+ 5
825......	1	19 15.5	0.803	+0.057	11.2	11.78	+ 6
	2	17.5	0.804	+0.058	11.2	11.78	+14
	3	19.5	0.806	+0.060	11.0	11.69	+13
	4	21.5	0.807	+0.061	10.7	11.57	+ 7
	5	23.5	0.808	+0.062	10.1	11.35	−12
827......	1	19 49.5	0.826	+0.080	8.6	10.88	+ 1
	2	51.5	0.827	+0.081	8.6	10.88	+ 4
	3	53.5	0.828	+0.082	8.5	10.84	+ 2
	4	55.5	0.830	+0.084	8.3	10.76	− 1
	5	57.5	0.831	+0.085	8.2	10.72	− 4
829......	1	20 22.5	0.849	+0.103	7.0	10.46	+ 5
	2	24.5	0.850	+0.104	6.8	10.40	+ 2
	3	26.5	0.852	+0.106	6.8	10.40	+ 4
	4	28.5	0.853	+0.107	6.4	10.26	− 9
	5	30.5	0.854	+0.108	6.6	10.33	− 1

TABLE XI—*Continued*

Plate	Exposure	G.M.T.		Phase	s	Mag.	O−C
			PHOTOVISUAL RESULTS				
P 814	1	$15^{h}41^{m}5$	$0^{d}654$	$-0^{d}092$	11.4	10.98	0
	2	45.5	0.657	−0.089	11.7	11.07	+ 4
	3	49.5	0.660	−0.086	11.8	11.11	+ 1
	4	53.5	0.662	−0.084	11.7	11.07	− 7
816	1	16 28.5	0.686	−0.060	13.2	11.85	+ 9
	2	32.5	0.689	−0.057	13.0	11.77	−17
	3	36.5	0.692	−0.054	13.4	11.92	− 5
	4	40.5	0.694	−0.052	13.8	12.04	− 7
818	1	17 2.5	0.710	−0.036	15.7	12.75	−12
	2	6.5	0.713	−0.033	15.6	12.71	−34
	3	10.5	0.715	−0.031	16.2	12.91	−25
	4	14.5	0.718	−0.028	16.5	13.00	−23
820	1	17 43.5	0.738	−0.008	17.2	13.25	+ 2
	2	47.5	0.741	−0.005	16.9	13.14	− 9
	3	51.5	0.744	−0.002	17.4	13.32	+ 9
	4	55.5	0.747	+0.001	17.2	13.25	+ 2
822	1	18 17.5	0.762	+0.016	17.8	13.18	− 5
	2	21.5	0.765	+0.019	17.8	13.18	− 5
	3	25.5	0.768	+0.022	18.1	13.30	+ 7
	4	29.5	0.771	+0.025	17.9	13.21	− 2
824	1	18 50.5	0.785	+0.039	14.6	12.61	− 6
	2	54.5	0.788	+0.042	14.4	12.53	− 2
	3	58.5	0.791	+0.045	14.2	12.44	+ 4
	4	19 2.5	0.794	+0.048	13.8	12.26	− 2
826	1	19 31.5	0.813	+0.067	12.7	11.66	− 1
	2	35.5	0.816	+0.070	12.2	11.48	− 4
	3	39.5	0.819	+0.073	12.5	11.59	+ 5
	4	43.5	0.821	+0.075	11.9	11.36	− 1
828	1	20 4.5	0.836	+0.090	10.7	10.97	− 3
	2	8.5	0.839	+0.093	10.7	10.97	+ 1
	3	12.5	0.842	+0.096	10.3	10.84	− 6
	4	16.5	0.845	+0.099	10.6	10.94	+10
830	1	20 37.0	0.859	+0.113	10.6	10.50	−13
	2	40.0	0.861	+0.115	11.1	10.66	+ 6
	3	43.0	0.863	+0.117	11.5	10.79	+22
	4	46.0	0.865	+0.119	11.0	10.62	+ 8

Both the photographic and the photovisual light-curves are defined for an interval of about a tenth of a day on either side of the minimum, so that the epoch is reasonably well established by both. The value, 1912, September 10, $17^{h}53^{m}5$ G.M.T., was given by both curves. Reduced to the sun, the result is, September 10, $17^h 54^m.5$, or J.D. 2419656.7461 G.M.T. The representation of the minimum by the elements of the first paper is exact. The representation of the visual observations by Lehnert[1] is less satisfactory, however, as each of the three minima observed by him give the correction $O-C=+0^d.006$. A deviation in the same direction is also shown by the minimum observed visually by Mr. Harlow Shapley at Princeton in June 1912, and kindly communicated by letter. The correction in this instance is $+0^d.003$.

Both series of photographic observations, and the photovisual results of the latter series were grouped into the normal places shown in Table XII for the formation of mean light-curves. As all of the data thus far accumulated, including the Laws Observatory visual measures, indicate that the light-curve is symmetrical, the results for the two branches were combined in deriving the normal places. The resulting curves are shown in Fig. 1, and their ordinates are given in the second and third columns of Table XIII. The representation of the observations by the curves is indicated by the residuals in the last column of Table XI. The average deviation for the photographic series is ±0.057 mag.; for the photovisual, ±0.077 mag. Omitting plate 818, for which the results are discordant, the average deviation for the photovisual observations becomes the same as for the photographic.

The limits and the amounts of variation, and the extreme color indices are:

	Photographic	Photovisual	Color Index
Maximum	9.64	9.98	−0.34
Minimum	13.46	13.23	+0.23
Amplitude	3.82	3.25	0.57

The two series of photographic observations agree closely in the values given for the photographic range. The photovisual range differs considerably from the visual value of 2.96 mags. found by Shapley on June 21, 1912, with a photometer of the polarizing type. Part of this difference may be due to the lack of red-sensitiveness in the Cramer "Iso" plate, which for stars of more advanced spectral types can scarcely be expected to give exact agreement with normal visual magnitudes. Both series of observations are in agreement, however, in indicating a smaller value for the visual

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[1] *Astronomische Nachrichten*, **191**, 201, 1912.

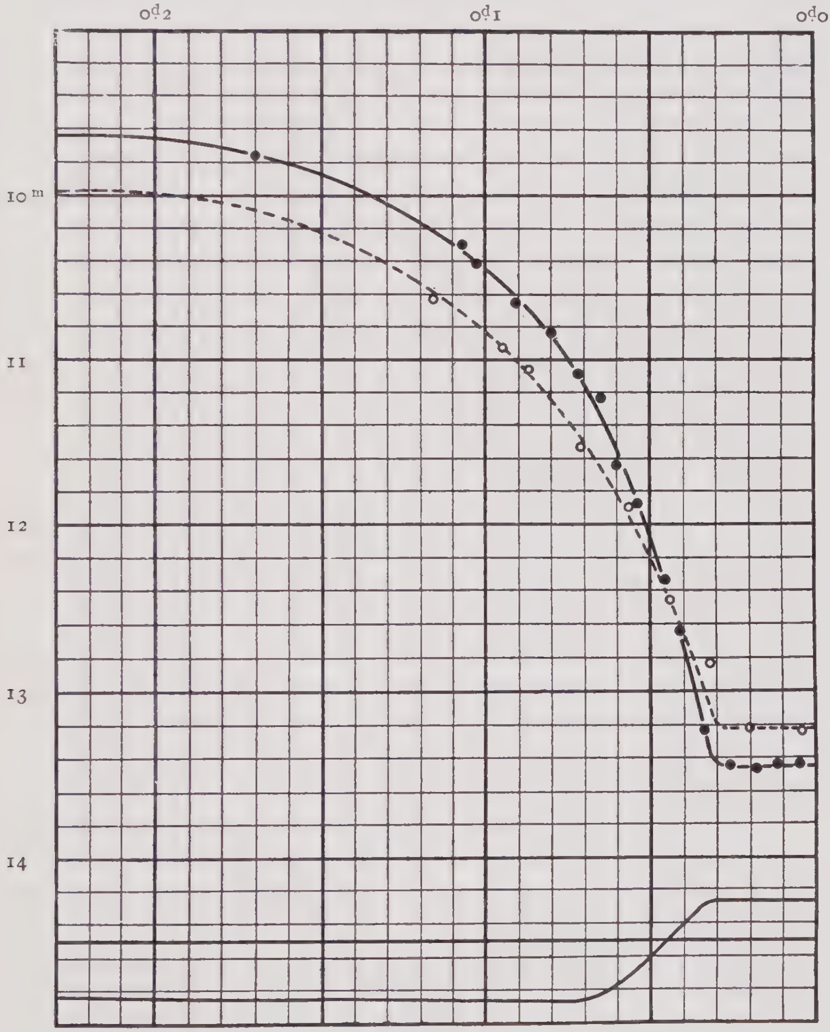

FIG. 1.—Photographic and photovisual light-curves for *RR Draconis*. The latter is the broken curve. The variation in the color index is shown in the lower part of the figure.

range, and there can be no doubt of the reality of the difference in the photographic and visual results.

TABLE XII

NORMAL PLACES FOR MEAN LIGHT-CURVE

PHOTOGRAPHIC				PHOTOVISUAL			
Phase	Mag.	O−C	No. Obs.	Phase	Mag.	O−C	No. Obs.
$0\overset{\mathrm{d}}{.}005$....	13.45	− 1	6	$0\overset{\mathrm{d}}{.}004$	13.24	+ 1	4
12....	13.45	− 1	7	20	13.22	− 1	4
18....	13.48	+ 2	7	32	12.84	−25	4
26....	13.44	− 2	7	44	12.46	0	4
34....	13.24	0	7	56	11.90	− 6	4
41....	12.64	0	6	71	11.52	+ 2	4
46....	12.33	0	6	87	11.06	0	4
54....	11.88	0	6	95	10.93	+ 2	4
60....	11.65	+ 9	6	116	10.64	+ 5	4
65....	11.24	−10	6	0.220	9.98	0	4
72....	11.08	0	6	.....	.....	....	..
80....	10.84	− 3	7	.....	.....	....	..
91....	10.65	+ 3	7	.....	.....	....	..
103....	10.42	+ 1	7	.....	.....	....	..
107....	10.30	− 4	6	.....	.....	....	..
170....	9.76	0	4	.....	.....	....	..
0.220....	9.64	0	..	.....	.....	....	..

TABLE XIII

MEAN LIGHT-CURVES AND COLOR INDEX OF *RR Draconis*

PHASE	MAGNITUDE		COLOR INDEX		PHASE	MAGNITUDE		COLOR INDEX	
	Photographic	Photovisual	Mt. W.	Laws Obs.		Photographic	Photovisual	Mt. W.	Laws Obs.
≦$0\overset{\mathrm{d}}{.}025$..	13.46	13.23	+23	....	$0\overset{\mathrm{d}}{.}090$..	10.65	11.00	−35	−33
30..	13.43	13.20	+23	....	100..	10.45	10.81	−36	−34
35..	13.14	12.94	+20	−10	110..	10.30	10.66	−36	−33
40..	12.73	12.63	+10	−13	120..	10.17	10.53	−36	−34
45..	12.40	12.40	0	−17	130..	10.07	10.42	−35	−34
50..	12.08	12.18	−10	−22	140..	9.98	10.31	−33	−33
55..	11.80	12.00	−20	−27	150..	9.89	10.23	−34	−34
60..	11.56	11.82	−26	−21	160..	9.82	10.16	−34	−34
65..	11.34	11.67	−33	−34	170..	9.76	10.10	−34	−34
70..	11.16	11.52	−36	−35	180..	9.71	10.05	−34	−34
75..	11.00	11.37	−37	−36	190..	9.68	10.02	−34	−34
80..	10.87	11.24	−37	−37	200..	9.66	10.00	−34	−34
85..	10.76	11.11	−35	−33	210..	9.65	9.99	−34	−34
0.090..	10.65	11.00	−35	−33	≧0.220..	9.64	9.98	−34	−34

The variation in the color index is shown by the curve in the lower part of Fig. 1, and the numerical values are given in the fourth column of Table XIII. The color index resulting from the comparison of the photographic results with the Laws Observatory visual light-curve in Table I of the first paper is also shown in Table XIII, in the last column. For this comparison the zero point of the visual curve was made to coincide with that of the photovisual results. An examination of the two series of values shows that for phase values greater than $0^{d}.060$ the three curves are practically identical. For values less than $0^{d}.060$ the Laws Observatory curve lies between the other two.

The photographic curve is probably well determined, and the same may be said of the photovisual curve between the phase values $0^{d}.050$ and $0^{d}.125$. The two points on the latter curve within the interval of constant minimum brightness are also probably reliable, but the intermediate portion of the curve is uncertain. It is impossible to improve the representation of the normal point at $0^{d}.032$ without leading to improbable values of the color index. On the other hand, there is no obvious reason why this point should be discordant, for plate 818, upon which it is based, is apparently equal in quality to the others. An examination of the residuals shows that they may be slightly reduced by applying a correction of $+0^{d}.002$ to the adopted epoch, but this raises difficulties with the photographic curve, unless we admit the possibility of a difference in the times of the photographic and photovisual minima. Although the modification of the photovisual epoch would reduce the average residual and lead to a correction for the adopted elements in the direction of that required by the visual observations of Lehnert and Shapley, it seems best to let the results stand as they are for the present.

If the photographic magnitudes be based upon the Mount Wilson system referred to above, it is to be noted that the maximum and minimum limits of variation become 10.01 and 13.83 mags., respectively; and that the extreme color indices are then +0.03 and +0.60. The corresponding spectrum at minimum is F5, and, as the minimum is a total eclipse of the bright body by the larger and darker companion, this value is to be assigned to the fainter object. The corresponding modifications in the photographic mean light-curve and in the color indices in Tables XII and XIII are made by adding the value 0.37 mag. throughout. The effect upon the curves in Fig. 1 would be to displace the photographic curve downward, and that of the color index upward, by this amount.

But quite independently of any uncertainty as to the spectrum, the investigation shows that the darker component of the system is redder than the brighter by an amount corresponding to 1.3 times the interval separating successive spectral classes; if Shapley's value of the visual range be used, the excess of redness is measured by nearly two spectral classes. The result is one of very great interest, for Shapley, in his investigation of the orbits of eclipsing binaries, has brought forth strong evidence that the darker components of systems of the type of *RR Draconis* are much less dense than their brighter companions, and, hence, presumably mark an earlier stage in stellar evolution. In view of this fact, the exact nature of the spectrum of the darker components of such systems becomes immediately a matter of the greatest interest. Should it appear that we are justified in assigning spectral classes on the basis of the ordinary relations between color index and spectrum, we should arrive at the very significant result that at least some of the so-called advanced spectral types are very probably to be associated with the earlier stages of stellar development. Such a possibility has of course long been recognized, but thus far definite evidence has not been procurable. It is obviously impossible to observe spectroscopically an object as faint as *RR Draconis* at minimum, but there are other *Algol* variables whose examination should prove profitable.

I am greatly indebted to Miss High of the computing division of the observatory for the very careful measurement of the plates upon which the above results are based.

Mount Wilson Solar Observatory
December 16, 1912

Contributions from the Mount Wilson Solar Observatory, No. 69
Reprinted from the *Astrophysical Journal*, Vol. XXXVII, pp. 322–353

RADIAL MOTION IN SUN-SPOTS

I. THE DISTRIBUTION OF VELOCITIES IN THE SOLAR VORTEX

By CHARLES E. ST. JOHN

In the spring of 1909 Mr. Evershed announced the remarkable discovery of the displacement of the Fraunhofer lines in the penumbrae of sun-spots. In brief, he found that practically all the lines of the reversing layer are shifted and that the stronger lines appear less affected than the weaker. He advanced the hypothesis that the displacements are due to the radial movement outward and tangential to the solar surface of the gases of the reversing layer. From his observations he concluded that the motion is accelerated outward but ceases abruptly at the limits of the penumbrae, that the movement is confined to the reversing layer, that the gases of the higher chromosphere do not share in the movement, but, on the contrary, show a tendency to move inward, and that the maximum velocity indicated by the majority of the lines is 1.57 km per second.[1]

In the summer of 1910 I began an extended investigation of the subject, using the spectrograph of the 60-foot tower telescope. By means of a simple occulting device, the spectra of the edges of the penumbrae directed toward the center and the limb of the sun, respectively, were obtained juxtaposed upon the photographic plate; and in what follows these edges will be referred to simply as the center and limb edges. The two diagrams show the details of the arrangement and the manner of using it. In position 1 of the occulting device the limb edge of the penumbra is tangent to the edge of the occulting bar at the point directly over the slit (*a*), which is parallel to the radius of the solar image passing through the spot. After making an exposure, the occulting bar is moved until the fiducial line (*c*) is directly over the slit, and the image of the sun is moved parallel to the slit until the center edge of the penumbra is tangent to the central line at the point (*d*). The occulting bar is then moved into position 2, and the second exposure made. In the procedure described, the spectrum of the spot was not photographed, but by placing the center edge of the penumbra tangent to the edge of the occulting bar in its first position and by a similar change in the second position, the spectra of the limb edge and the center edge of the penumbra are side by side along the center of the plate with a spectrum of the spot on either side. This has the advantage that the distance of the point measured from the center of the spot can be determined, and the whole course of the displaced line can be examined; but for purposes of measurement, the first plan was found more satisfactory. The displacement was doubled in either case, as on one edge of the penumbra the lines are shifted to the red, and on the other to the violet. The positions of the spots on a solar image 170 mm in diameter varied from 10 to 45 mm from the limb. The usual course of the line on such plates shows no sharp break and the displacement does not suddenly cease at the periphery of the penumbra, but the line gradually returns to its normal course. This differs from Mr. Evershed's observation, and seems to remove one great difficulty in explaining the displacement as due to motion.

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[1] *Kodaikanal Observatory Bulletin*, No. XV; *Kodaikanal Observatory Memoirs*, 1, Pt. 1.

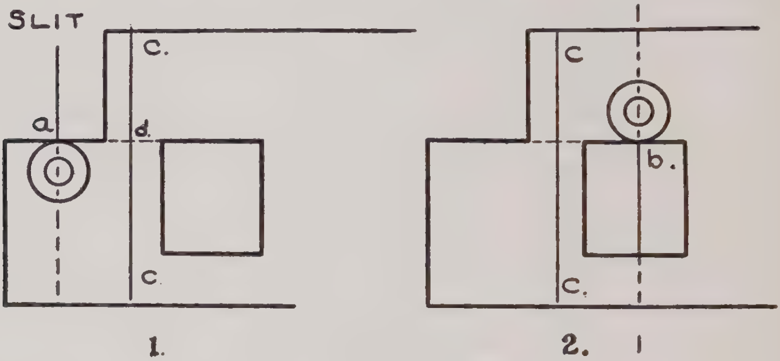
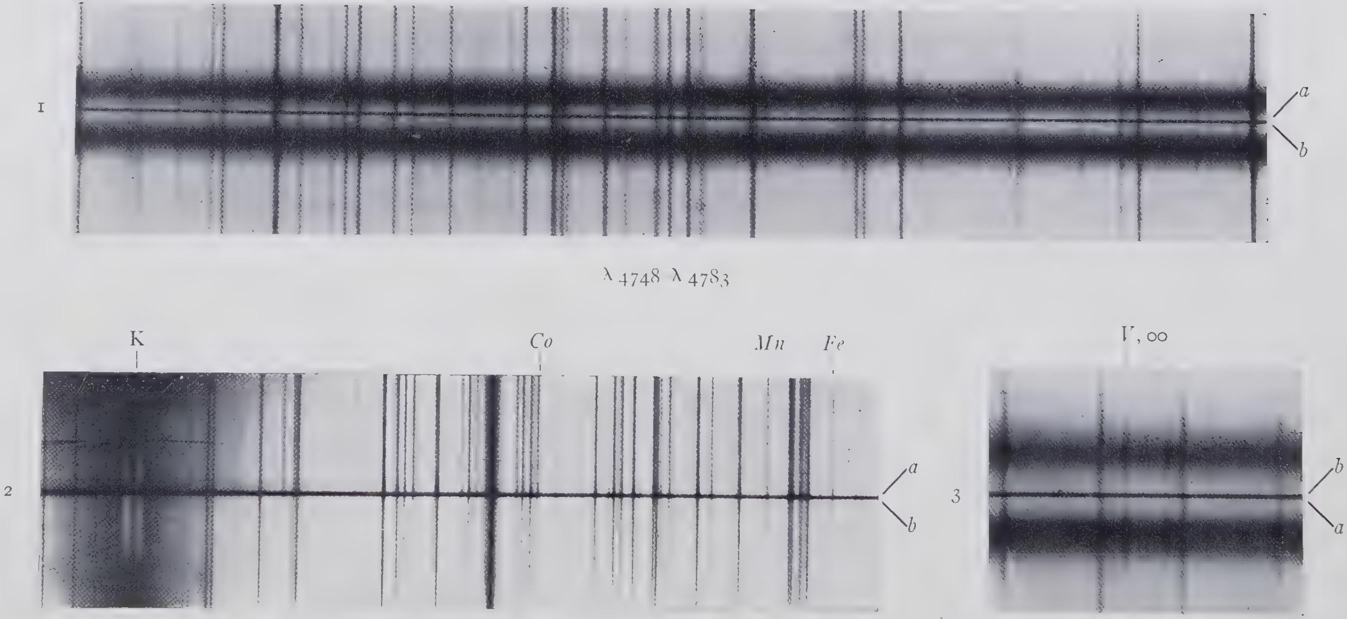


FIG. 1.—Occulting device

There was a question whether the slight shifting of the solar image would not of itself introduce displacements caused by the change in the illumination of the grating. This was tested by

PLATE XXIV



λ 4748 λ 4783

λ 3931–λ 3953

λ 4829–λ 4834

Spectrum of the Edge of the Penumbra

a, Edge directed toward the limb. *b*, Edge directed toward the center of the disk

1. Relative displacements of strong and weak lines, indicating different velocities of outflow
2. Displacement of the K line of calcium, showing inflow
3. Large displacement and great strengthening of *V* lines of intensity ∞

measurements of the atmospheric lines wherever they appeared upon the plate, and the absence of any effect due to this cause or to instrumental displacements completely justified the method. On 54 plates the mean displacement of the atmospheric lines was +0.0003 Å.

For measurement, the plate was first adjusted so that the edges of the spectra where they were opposed moved parallel to the screw. The cross-hair of the microscope was fixed parallel to the normal direction of the lines by setting upon the two parts of the line on each side of the division and far enough from the penumbra to be undisturbed by the radial motion. The field of the microscope was sufficiently flat to allow of this. Measurements were made upon the points of the line that were equally distant from the horizontal cross-hair, which was central with respect to the two spectra, and these distances were equal for all lines. The plates in the violet and green were taken in the third-order spectrum and those in the yellow and the red in the second order, the dispersion in the two cases being 1 mm=0.56 Å. and 1 mm=0.86 Å. It was found that for such lines as D_1 and D_2 and H_α, the second order gained in accuracy over the third as much as it lost in dispersion, and the requisite intensity of the spectra was obtained by much shorter exposure time.

Observations were obtained upon the following regular spots which are identified by the Greenwich numbers. The diameters of the umbrae and penumbrae are given for the central meridian on an image 170 mm in diameter.

Spot No.	C.M. G.M.T.	Umbra	Penumbra	Spot No.	C.M. G.M.T.	Umbra	Penumbra
		mm	mm			mm	mm
6847..	1910 May 18.6	1.1	2.3	6942..	1911 Apr. 27.7	0.9	2.5
6864..	July 6.3	1.7	4.0	6944..	Apr. 28.7	1.1	3.0
6874..	Aug. 9.5	1.7	4.0	6945..	Apr. 28.9	0.5	1.5
6880..	Sept. 5.8	1.2	3.0	6951..	May 30.8	1.0	2.5
6886..	Oct. 26.9	0.9	2.5	6972..	Nov. 27.1	0.9	2.0
6940..	1911 Apr. 9.3	1.0	3.0	Mean		1.1	3.0

In laying out the program for what was expected to be a preliminary survey, it was not at first clear what lines would prove of the greatest interest. An examination of the blue region studied by Mr. Evershed showed at once that the list should embrace a large number of lines of as diverse character as possible. The lines were selected on the following bases:

a) As many elements as possible to be included, in fact, 27 substances are represented in the list.

b) Lines known to originate in the higher levels of the chromosphere such as H, K, H_a, and the strongest lines of magnesium, aluminium, and iron.

c) Elements of exceptionally high atomic weight, and rare elements, particularly barium, lanthanum, cerium, lead, ytterbium, neodymium, and niobium.

d) Lines covering a wide range of intensities for each element.

e) A very large number of lines of all intensities of some one element represented by many lines, such as iron.

f) Lines of peculiar interest, such as the enhanced lines, and lines belonging to different pressure groups.

The program has included 506 lines which fulfil the conditions indicated in sufficient numbers to permit statistical treatment, and they are distributed as follows: violet 268, blue-green 164, yellow-red 74.

In the first three columns of Table I are the wave-lengths, identifications, and intensities, as given in Rowland's table. The fourth column contains the absolute displacements in Ångströms reduced to the limb; the fifth column, the number of plates; and the sixth column, the mean deviations. These are not a measure of the accuracy of the measurements, but include the deviation from plate to plate, which is the larger element involved. The displacements vary rapidly with the distance from the edge of the penumbra, and, with the utmost possible care in guiding, the slit cannot be set and rigorously held upon the same point with respect to the edge of the penumbra, so that plates taken in quick succession give different absolute displacements, but for each plate (45 cm long) the relative displacements of the various lines upon the plate are in the proper relation. If the position of the slit is changed by a fifth of a millimeter, the point of observation on the sun for the mean positions of the spots is shifted 2000 km toward or away from the axis of the spot, and for such changes in distance the change in velocity is large. The seventh column under Δ′ requires a word of explanation. As has just been said, the absolute values for different plates vary. If, therefore, upon any given plate it has for any reason been impossible to measure the displacement of a line appearing upon the other plates, the omission of this line from the plate under consideration might appreciably affect the final mean if the plate as a whole showed displacements differing greatly from the mean of the other plates. The values under Δ′ are obtained in the following way: when the displacement of a line in the list has not been measured on a given plate because of some defect or lack of intensity or definition, an interpolated value for the displacement of the line on this plate has been used in determining the final mean. The interpolation was carried out as follows: considering only the lines common to all the plates, the ratio was found between the displacements on the given plate and the mean displacements on the other plates. This ratio is the operator by which the required displacement is found from the mean displacement of the same line on the other plates. The procedure not only eliminated the irregularities introduced by the omission of the line from one or more plates, but equalized the weights of the observations for neighboring lines. The mean values are the ones used in the discussion. As a matter of fact, the greater number of the displacements under Δ′ agree with those under Δ. Changes occur in the case of 97 out of 506 lines. In 63 cases the correction is ±0.001 Å., in 26 cases, ±0.002 Å., and in 8 cases, ±0.003 Å. The adjustments have a random distribution and produce no systematic effect. In the eighth column the displacements are reduced to λ 5000; and in the ninth column, under character and group, are given the grouping of the iron and titanium lines suggested by Gale and Adams,[1] with the addition of group *e* and the subdivision of group *d* suggested in a paper by Miss Ware and myself on the iron standards,[2] also the enhanced lines, and some probable blends.

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 58; *Astrophysical Journal*, **35**, 10–47, 1912.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 61; *Astrophysical Journal*, **36**, 14, 1912.

TABLE I

Relative Displacements of the Fraunhofer Lines at the Limb and Center Edges of the Penumbrae of Eccentrically Located Spots

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ′	Δ′ Reduced to λ 5000	Character or Group
3624.258...	*Ca*	3	+0.012	3	4	+0.012	+0.016	
3627.953...	*Co*	4	+0.016	3	3	+0.016	+0.022	
3628.967...	*La*	2	+0.019	3	11	+0.019	+0.026	
3629.877...	*Mn*	1	+0.017	3	5	+0.017	+0.023	
3630.045...	*Ni*	1	+0.024	3	3	+0.024	+0.033	
3631.124...	*Ca*	2	+0.016	3	4	+0.016	+0.022	
3639.943...	*Cr*	2	+0.017	3	4	+0.017	+0.023	
3646.335...	*Ti*	1	+0.012	3	3	+0.012	+0.016	
3649.137...	*Cr*	1	+0.014	3	2	+0.014	+0.019	
3652.691...	*Co*	3	+0.013	3	4	+0.013	+0.018	
3653.637...	*Ti*	5	+0.008	3	3	+0.008	+0.011	
3659.663...	*Fe*	5	+0.014	3	6	+0.014	+0.019	
3662.096...	*Ni*	3	+0.015	5	4	+0.015	+0.021	
3670.566...	*Ni*	5	+0.011	5	2	+0.011	+0.015	
3686.926...	*Cr*	1	+0.016	5	6	+0.016	+0.022	
3687.234...	*Fe*	3	+0.010	5	3	+0.010	+0.014	
3687.610...	*Fe*	6	+0.007	3	1	+0.007	+0.008	
3688.210...	*V*	1	+0.018	4	5	+0.018	+0.024	
3690.599...	*Fe*	2	+0.017	5	2	+0.017	+0.023	
3692.364...	*V*	1	+0.017	5	4	+0.017	+0.023	
3692.790...	*Fe*	2	+0.020	5	4	+0.020	+0.027	
3693.616...	*Co*	1	+0.021	5	9	+0.021	+0.028	
3694.344...	*Yt*	3	+0.020	5	6	+0.020	+0.027	
3694.576...	*La*	1	+0.027	5	3	+0.027	+0.036	
3695.194...	*Fe*	5	+0.013	5	1	+0.013	+0.017	
3697.567...	*Fe*	5	+0.012	4	5	+0.012	+0.016	
3698.744...	*Fe*	4	+0.014	5	3	+0.014	+0.019	
3699.283...	*Fe*	3	+0.019	5	4	+0.019	+0.026	
3701.234...	*Fe*	8	+0.007	4	6	+0.007	+0.009	
3702.170...	*Fe*	4	+0.019	4	2	+0.019	+0.025	
3702.639...	*Fe*	4	+0.017	5	4	+0.017	+0.023	
3704.603...	*Fe*	4	+0.016	5	3	+0.016	+0.021	
3704.840...	*V*	1	+0.016	5	3	+0.016	+0.022	
3706.363...	*Fe*	3	+0.018	3	4	+0.017	+0.023	
3707.186...	*Fe*	5	+0.014	5	7	+0.014	+0.019	
3707.600...	*Co*	2	+0.005	5	5	+0.005	+0.007	
3707.702...	*Ti*	2	+0.013	5	5	+0.013	+0.017	
3708.964...	*Co*	1	+0.015	5	5	+0.015	+0.020	
3709.389...	*Fe*	8	+0.002	4	5	+0.002	+0.003	*b*
3710.431...	*Y*	3	+0.015	5	6	+0.016	+0.020	
3711.364...	*Fe*	4	+0.014	5	4	+0.014	+0.019	
3711.552...	*Fe*	3	+0.015	5	1	+0.015	+0.020	
3716.591...	*Fe*	7	+0.012	4	2	+0.012	+0.016	
3717.539...	*Ti*	2	+0.017	5	3	+0.017	+0.023	
3718.554...	*Fe*	4	+0.015	5	1	+0.015	+0.020	
3720.084...	*Fe*	40	+0.003	3	1	+0.003	+0.004	
3724.970...	*Ni*	1	+0.018	5	8	+0.018	+0.024	
3879.716...	*CN*	1	+0.015	9	7	+0.015	+0.020	
3879.824...	*CN*	0	+0.021	7	5	+0.021	+0.028	
3880.105...	*CN*	1	+0.012	7	6	+0.012	+0.015	

TABLE I—*Continued*

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ'	Δ' Reduced to λ 5000	Character or Group
3880.205...	*CN*	0	+0.017	5	6	+0.017	+0.022	
3882.267...	*CN*	1	+0.014	7	4	+0.014	+0.019	
3895.119...	*Co*	3	+0.012	9	5	+0.012	+0.015	
3895.377...	*Ti*	2	+0.019	7	5	+0.020	+0.025	
3895.583...	*Mn*	3	+0.008	7	6	+0.008	+0.010	
3895.803...	*Fe*	7	+0.004	9	8	+0.004	+0.005	*a*
3897.596...	*Fe*	2	+0.009	9	6	+0.009	+0.012	
3898.032...	*Fe*	3	+0.007	9	8	+0.007	+0.009	
3898.531...	*Mn*	2	+0.014	9	7	+0.014	+0.018	
3899.171...	*Fe*	3	+0.013	9	5	+0.013	+0.017	
3901.114...	*Ti*	1	+0.017	8	8	+0.017	+0.021	*a*
3902.399...	*V*	3	+0.012	9	6	+0.012	+0.015	
3904.926...	*Ti*	3	+0.013	9	7	+0.013	+0.017	*a*
3905.660...	*Si*	12	0.000	9	5	0.000	0.000	Enh.-*Cr*?
3906.438...	*Co*	2	+0.010	9	6	+0.010	+0.013	
3906.628...	*Fe*	10	+0.003	9	5	+0.003	+0.004	*a*
3908.900...	*Cr*	4	+0.011	9	8	+0.011	+0.014	
3911.963...	*Sc*	2	+0.013	8	4	+0.013	+0.017	
3913.123...	*Ni*	2	+0.016	8	6	+0.016	+0.020	
3916.879...	*Fe*	5	+0.009	9	5	+0.009	+0.011	
3933.825...	K_3		−0.050	9	16	−0.050	−0.064	
3933.825...	K_2		−0.036	9	14	−0.036	−0.046	
3941.637...	*Cr*	3	+0.014	11	6	+0.014	+0.018	
3941.878...	*Co*	2	+0.015	11	7	+0.015	+0.019	
3944.160...	*Al*	15	+0.001	12	6	+0.001	+0.001	
3947.142...	*Fe*	3	+0.011	12	4	+0.011	+0.014	
3947.522...	?	2	+0.014	4	7	+0.014	+0.018	
3947.675...	*Fe*	4	+0.009	5	3	+0.009	+0.011	
3947.918...	*Ti*	2	+0.011	11	7	+0.013	+0.016	*a*
3948.818...	*Ti*	4	+0.009	14	5	+0.009	+0.011	*a*
3948.925...	*Fe*	4	+0.009	14	7	+0.009	+0.011	
3949.039...	*Ca*	1	+0.017	11	6	+0.018	+0.022	
3950.102...	*Fe*	15	+0.010	14	5	+0.010	+0.013	
3950.497...	*Y*	5	+0.013	14	5	+0.013	+0.016	
3956.603...	*Fe*	4	+0.010	16	5	+0.010	+0.013	
3956.879...	*Fe*	6	+0.009	15	5	+0.009	+0.011	
3958.073...	*Co*	2	+0.017	15	5	+0.018	+0.021	
3958.877...	*Fe*	1	+0.022	7	5	+0.021	+0.026	
3960.422...	*Fe*	4	+0.014	16	5	+0.014	+0.017	
3961.674...	*Al*	20	0.000	16	6	0.000	0.000	
3962.995...	*Ti*	3	+0.012	16	5	+0.012	+0.015	*a*
3963.831...	*Co*	3	+0.010	16	5	+0.010	+0.013	
3968.825...	H_3		−0.049	15	15	−0.049	−0.062	
3968.825...	H_2		−0.033	14	21	−0.033	−0.042	
3969.413...	*Fe*	10	+0.004	16	8	+0.004	+0.005	
3971.475...	*Fe*	5	+0.008	16	4	+0.008	+0.010	
3974.774...	*Ni*	2	+0.015	8	5	+0.014	+0.018	
3977.891...	*Fe*	6	+0.010	17	5	+0.010	+0.013	*b*
3980.779...	*Fe*	1	+0.014	9	6	+0.014	+0.018	
3981.248...	*Fe*	2	+0.017	10	5	+0.017	+0.021	
3981.917...	*Ti*	4	+0.013	9	5	+0.013	+0.016	*a*
3982.745...	*Y*	3	+0.013	9	5	+0.013	+0.016	
3984.294...	*Mn*	2	+0.021	9	7	+0.021	+0.026	

TABLE I—*Continued*

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ′	Δ′ Reduced to λ 5000	Character or Group
3984.479...	*Cr*	2	+0.024	9	7	+0.024	+0.030	
3986.321...	*Fe*	3	+0.011	8	3	+0.011	+0.014	
3989.912...	*Ti*	4	+0.008	9	6	+0.008	+0.010	*a*
3990.011...	*Fe*	3	+0.012	11	7	+0.012	+0.015	
3990.525...	*Fe*	2	+0.016	11	4	+0.016	+0.020	
3991.580...	*Fe*	1	+0.020	11	6	+0.020	+0.025	
3993.246...	*Fe*	2	+0.026	10	8	+0.025	+0.031	
3994.265...	*Fe*	4	+0.015	11	8	+0.015	+0.019	
3994.828...	*Nd?*	2	+0.018	11	7	+0.018	+0.022	
3995.463...	*Co*	5	+0.011	11	5	+0.011	+0.014	
3995.899...	*La*	1 N	+0.014	11	9	+0.014	+0.018	
3996.140...	*Fe*	3	+0.015	12	8	+0.015	+0.019	
3997.115...	*Fe*	2	+0.019	12	9	+0.019	+0.024	
3997.547...	*Fe*	4	+0.012	12	6	+0.012	+0.015	*b*
3998.053...	*Co*	4	+0.017	12	10	+0.017	+0.021	
3998.205...	*Fe*	4	+0.014	12	7	+0.014	+0.018	
3998.790...	*Ti*	4	+0.012	12	5	+0.012	+0.015	*a*
4000.403...	*Fe*	2	+0.023	12	11	+0.023	+0.029	
4000.611...	*Fe*	2	+0.016	12	7	+0.016	+0.020	
4001.595...	*Cr*	1	+0.022	11	8	+0.021	+0.026	
4001.814...	*Fe*	3	+0.016	12	9	+0.016	+0.020	
4006.304...	*Ni*	1	+0.024	12	10	+0.024	+0.030	
4006.464...	*Fe*	2	+0.020	12	9	+0.020	+0.025	
4006.776...	*Fe*	3	+0.015	11	6	+0.017	+0.021	
4010.927...	*Fe*	2	+0.022	12	9	+0.022	+0.028	
4011.080...	*Fe*	2	+0.026	12	8	+0.026	+0.022	
4013.964...	*Fe*	5	+0.020	12	9	+0.020	+0.025	
4016.574...	*Fe*	2	+0.022	12	10	+0.022	+0.027	
4018.420...	*Fe*	3	+0.022	12	11	+0.022	+0.027	
4020.547...	*Sc*	1	+0.014	11	8	+0.014	+0.017	
4021.057...	*Co*	3	+0.018	12	7	+0.018	+0.022	
4023.834...	*Sc*	2	+0.026	12	7	+0.026	+0.031	
4024.726...	*Ti*	3	+0.016	12	7	+0.016	+0.019	*a*
4035.752...	*Co*	2	+0.015	10	4	+0.016	+0.019	
4055.701...	*Mn*	6	+0.018	12	9	+0.018	+0.021	Enh.–*Fe?*
4059.081...	*Mn*	3	+0.018	12	6	+0.018	+0.021	
4063.759...	*Fe*	20	0.000	12	10	0.000	0.000	*b*
4066.524...	*Co*	2	+0.020	12	8	+0.020	+0.024	
4070.431...	*Mn*	3	+0.023	12	9	+0.023	+0.028	
4077.885...	*Sr*	8	−0.002	12	7	−0.002	−0.002	Enh.
4078.631...	*Ti*	3	+0.018	10	7	+0.017	+0.021	*a*
4079.570...	*Mn*	3	+0.018	12	9	+0.018	+0.022	
4083.095...	*V–Mn*	4	+0.020	12	10	+0.020	+0.024	
4086.861...	*La*	1	+0.026	12	12	+0.026	+0.031	
4095.094...	*Ca?*	4	+0.020	12	9	+0.020	+0.024	
4099.941...	*V*	2	+0.025	12	5	+0.025	+0.030	
4102.000...	*Hδ*	40	−0.004	11	14	−0.004	−0.005	
4103.097...	*Si–Mn*	5	+0.017	12	7	+0.017	+0.020	
4109.609...	*Nd?*	1	+0.016	12	6	+0.016	+0.019	
4110.691...	*Co*	4	+0.016	11	7	+0.016	+0.019	
4111.509...	*Co*	1	+0.028	12	11	+0.028	+0.034	
4116.859...	*Nd?*	1	+0.027	9	17	+0.025	+0.030	
4118.934...	*Co*	4	+0.013	12	5	+0.013	+0.016	

TABLE I—*Continued*

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ′	Δ′ Reduced to λ 5000	Character or Group
4123.384...	*La*	2	+0.024	11	14	+0.023	+0.028	
4129.337...	*Ce*–	3	+0.022	12	7	+0.022	+0.026	
4130.804...	*Ba*	2	+0.027	11	10	+0.027	+0.033	Enh.
4131.271...	*Mn*	1	+0.027	11	11	+0.026	+0.031	
4132.100...	*V*	2	+0.011	10	8	+0.011	+0.013	
4132.235...	*Fe*	10	+0.002	9	7	+0.002	+0.002	*b*
4133.755...	*Fe*	2	+0.022	12	9	+0.022	+0.026	
4134.840...	*Fe*	5	+0.014	11	5	+0.014	+0.017	*b*
4136.678...	*Fe*	4	+0.023	11	7	+0.023	+0.028	
4137.156...	*Fe*	6	+0.016	12	8	+0.016	+0.019	
4137.809...	*Ce*	1	+0.014	12	10	+0.014	+0.017	
4142.330...	*Cr*	2	+0.026	12	11	+0.026	+0.031	
4142.624...	*Cr*	2	+0.027	4	12	+0.026	+0.031	
4147.645...	*Mn*	1	+0.023	12	9	+0.023	+0.028	
4149.360...	*Zr*	2	+0.016	12	9	+0.016	+0.019	
4150.608...	*Co*	1	+0.017	9	6	+0.017	+0.020	
4157.948...	*Fe*	5	+0.015	14	9	+0.015	+0.018	
4161.961...	*Sr*	1	+0.025	13	10	+0.025	+0.030	
4167.884...	*CN*	1	+0.026	9	8	+0.027	+0.032	
4168.133...	*Ni*	2	+0.020	14	10	+0.020	+0.024	
4179.025...	*Fe*	3	+0.018	17	9	+0.018	+0.022	
4180.970...	*CN*	2	+0.017	16	10	+0.017	+0.020	
4183.480...	*Zr*	1	+0.022	8	12	+0.024	+0.029	
4183.619...	*Z*	2	+0.024	12	10	+0.024	+0.029	
4184.472...	*Ti*	2	+0.022	16	11	+0.022	+0.026	
4195.006...	*Cr*	1	+0.020	7	7	+0.020	+0.024	
4196.699...	*La*	2	+0.023	16	9	+0.024	+0.029	
4196.837...	*Fe*	1	+0.020	16	10	+0.020	+0.024	
4197.257...	*CN*	2	+0.021	16	10	+0.021	+0.025	
4204.163...	*La*	4	+0.020	8	9	+0.020	+0.025	
4216.136...	*CN*	1	+0.022	13	8	+0.022	+0.026	
4225.020...	*Cr*	2	+0.021	13	10	+0.021	+0.025	
4226.904...	*Ca*	20	−0.002	11	7	−0.002	−0.002	
4227.606...	*Fe*	4	+0.010	11	10	+0.010	+0.012	
4232.111...	*Nb?*	1	+0.029	10	11	+0.030	+0.035	
4233.328...	*Mn, Fe*	4	+0.018	10	10	+0.017	+0.020	
4233.772...	*Fe*	6	+0.012	10	10	+0.012	+0.014	*d*
4236.112...	*Fe*	8	+0.003	11	7	+0.003	+0.003	*d*
4236.429...	*Ni*	1	+0.024	10	14	+0.024	+0.028	
4238.970...	*Fe*	5	+0.015	10	6	+0.015	+0.018	
4240.872...	*Cr*	1	+0.022	9	6	+0.022	+0.026	
4246.996...	*Sc*	5	+0.013	8	12	+0.013	+0.015	
4250.287...	*Fe*	8	+0.014	7	7	+0.014	+0.016	*c*
4253.157...	*Mn*	1	+0.027	6	6	+0.028	+0.033	
4254.505...	*Cr*	8	+0.008	7	6	+0.008	+0.009	
4257.815...	*Mn*	2	+0.022	6	11	+0.023	+0.027	
4258.477...	*Fe*	2	+0.022	7	12	+0.022	+0.026	
4260.640...	*Fe*	10	+0.003	5	4	+0.003	+0.003	*c*
4262.142...		1	+0.024	6	12	+0.023	+0.027	
4266.080...	*Mn*	2	+0.024	7	11	+0.024	+0.028	
4271.325...	*Fe*	6	+0.009	7	4	+0.009	+0.010	
4271.934...	*Fe*	15	−0.005	7	4	−0.005	−0.006	*b*
4273.643...	*Zr*	2N	+0.021	7	9	+0.021	+0.024	

TABLE I—*Continued*

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ′	Δ′ Reduced to λ 5000	Character or Group
4274.746...	*Ti*	2	+0.016	7	10	+0.016	+0.019	
4274.958...	*Cr*	7	+0.002	7	9	+0.002	+0.002	
4277.544...	*Cr*	0	+0.023	4	10	+0.026	+0.030	
4281.257...	*Mn*	2	+0.018	7	8	+0.018	+0.021	
4282.565...	*Ti*	5	+0.012	7	7	+0.012	+0.014	
4283.169...	*Ca*	4	+0.017	7	9	+0.017	+0.020	
4284.382...	*Cr*	2	+0.023	7	10	+0.023	+0.027	Enh.
4284.838...	*Ni*	1	+0.030	7	13	+0.030	+0.035	
4287.158...	*La*	2	+0.017	6	13	+0.019	+0.022	
4287.566...	*Ti*	1	+0.026	7	8	+0.026	+0.031	*a*
4289.237...	*Ti*	2	+0.022	7	7	+0.022	+0.026	*a*
4289.525...	*Ca*	4	+0.015	7	7	+0.015	+0.018	
4290.377...	*Ti*	2	+0.013	7	10	+0.013	+0.015	Enh.
4291.630...	*Fe*	2	+0.015	7	8	+0.015	+0.018	*a*
4294.936...	*Zr*	2	+0.018	7	8	+0.018	+0.021	
4296.044...	*Ni*	1	+0.020	7	10	+0.020	+0.023	
4299.149...	*Ca*	3	+0.015	7	8	+0.015	+0.018	
4299.803...	*Ti*	2	+0.016	7	7	+0.016	+0.019	*a*
4300.211...	*Ti*	3	+0.007	7	4	+0.007	+0.008	Enh.
4300.732...	*Ti*	2	+0.018	7	11	+0.018	+0.021	*a*
4302.085...	*Ti*	2	+0.016	7	6	+0.016	+0.019	Enh.
4302.353...	*Fe*	2	+0.019	5	8	+0.019	+0.022	
4302.692...	*Ca*	4	+0.011	7	3	+0.011	+0.013	
4304.882...	*Zr*	0	+0.020	4	9	+0.020	+0.023	
4306.078...	*Ti*	4	+0.015	7	5	+0.015	+0.015	*a*
4313.034...	*Ti*	3	+0.010	6	6	+0.011	+0.013	Enh.
4314.248...	*Sc*	3	+0.016	7	7	+0.016	+0.018	
4314.964...	*Ti*	1	+0.026	5	8	+0.025	+0.029	*d?*
4315.138...	*Ti*	3	+0.009	6	5	+0.010	+0.011	
4320.907...	*Sc*	3	+0.017	7	9	+0.017	+0.020	
4325.152...	*Sc*	4	+0.012	7	7	+0.012	+0.014	
4325.939...	*Fe*	8	+0.006	7	7	+0.006	+0.007	*b*
4328.080...	*Fe*	2	+0.018	7	14	+0.018	+0.021	
4331.811...	*Ni*	2	+0.021	7	10	+0.021	+0.024	
4333.925...	*La*	1 N	+0.029	5	10	+0.026	+0.030	
4337.216...	*Fe*	5	+0.015	7	5	+0.015	+0.017	*b*
4338.084...	*Ti*	4	+0.014	7	5	+0.014	+0.016	Enh.
4338.430...	*Fe*	1	+0.025	6	10	+0.025	+0.029	
4340.634...	H_γ	20	−0.028	4	12	−0.029	−0.033	
4344.670...	*Cr*	4	+0.016	7	4	+0.016	+0.018	
4352.083...	*Ng*	5	+0.013	7	5	+0.013	+0.015	
4352.908...	*Fe*	4	+0.015	7	8	+0.015	+0.017	*b*
4359.784...	*Cr*	3	+0.018	7	11	+0.018	+0.021	
4359.907...	*Zr*	0	+0.016	4	9	+0.019	+0.022	
4369.941...	*Fe*	4	+0.018	6	9	+0.018	+0.021	*b*
4374.981...	*Zr*	0	+0.012	4	7	+0.015	+0.017	
4376.107...	*Fe*	6	+0.014	7	9	+0.014	+0.016	*a*
4377.948...	*Fe*	1	+0.030	7	12	+0.030	+0.034	
4379.396...	*V*	4	+0.016	7	8	+0.016	+0.018	
4380.326...	*Co*	2 N	+0.031	7	17	+0.031	+0.035	
4383.720...	*Fe*	15	−0.003	5	18	−0.003	−0.003	*b*
4385.548...	*Fe*	2	+0.021	7	12	+0.021	+0.024	Enh.
4387.220...	*Pb*	1 N	+0.026	7	10	+0.026	+0.030	Enh.

TABLE I—*Continued*

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ′	Δ′ Reduced to λ 5000	Character or Group
4390.149...	*V*	2	+0.020	7	10	+0.020	+0.023	
4400.555...	*Sc*	3	+0.016	7	9	+0.016	+0.018	
4400.738...	*V*	1	+0.021	7	8	+0.021	+0.024	
4404.927...	*Fe*	10	+0.003	4	8	+0.003	+0.003	*b*
4408.364...	*V*	2	+0.027	6	8	+0.027	+0.030	
4410.683...	*Ni*	2	+0.028	6	11	+0.026	+0.029	
4634.254...	*Cr*	2	+0.033	10	10	+0.032	+0.034	
4636.027...	*Fe*	2	+0.035	14	14	+0.035	+0.038	
4637.685...	*Fe*	5	+0.028	17	9	+0.028	+0.030	
4638.193...	*Fe*	4	+0.026	16	8	+0.027	+0.029	
4643.645...	*Fe*	4	+0.030	17	12	+0.030	+0.032	
4646.347...	*Cr*	5	+0.018	18	6	+0.018	+0.019	
4648.835...	*Ni*	4	+0.026	17	7	+0.026	+0.028	
4651.461...	*Cr*	4	+0.024	17	8	+0.024	+0.026	
4652.343...	*Cr*	5	+0.023	17	6	+0.023	+0.025	
4656.644...	*Ti*	3	+0.034	3	19	+0.034	+0.036	
4662.149...	*Fe?*	1	+0.030	3	11	+0.030	+0.032	
4667.626...	*Fe*	4	+0.012	3	6	+0.013	+0.013	
4667.768...	*Ti*	3	+0.027	17	8	+0.027	+0.029	*a*
4669.354...	*Fe*	3	+0.035	3	12	+0.035	+0.037	
4675.294...	*Ti*	1 N	+0.041	14	10	+0.040	+0.043	*a*
4678.347...	*Cd*	3 N	+0.039	16	7	+0.038	+0.041	
4679.027...	*Fe*	6	+0.023	18	10	+0.023	+0.025	
4679.409...	*Ni*	2	+0.038	12	11	+0.037	+0.039	Enh.
4680.317...	*Zn*	1	+0.028	10	8	+0.025	+0.027	
4682.088...	*Ti*	3	+0.029	18	8	+0.029	+0.031	
4683.745...	*Fe*	3	+0.029	3	5	+0.029	+0.031	
4685.452...	*Ca*	2 N	+0.034	18	10	+0.034	+0.036	
4686.395...	*Ni*	3	+0.035	17	10	+0.035	+0.037	
4688.357...	*Fe*	2	+0.036	3	7	+0.036	+0.038	
4701.714...	*Ni*	1	+0.038	17	9	+0.038	+0.040	
4703.177...	*Ng*	10	+0.010	17	11	+0.010	+0.011	
4703.994...	*Ni*	3	+0.035	17	13	+0.035	+0.037	
4705.131...	*Fe*	4	+0.038	3	4	+0.038	+0.040	
4708.196...	*Cr*	2	+0.033	38	33	+0.033	+0.035	
4708.846...	*Ti*	2	+0.028	15	13	+0.031	+0.033	Enh.
4709.896...	*Mn*	2	+0.031	18	9	+0.031	+0.033	
4715.946...	*Ni*	4	+0.026	18	10	+0.026	+0.028	
4718.601...	*Cr*	3	+0.040	18	12	+0.040	+0.042	
4722.342...	*Zn*	3	+0.036	18	12	+0.036	+0.038	
4728.732...	*Fe*	4	+0.037	3	5	+0.037	+0.039	
4730.897...	*Cr*	1	+0.039	15	9	+0.038	+0.040	
4731.984...	*Ni*	1	+0.030	3	4	+0.030	+0.032	
4732.640...	*Ni*	1	+0.038	3	4	+0.038	+0.040	
4733.779...	*Fe*	4	+0.027	18	16	+0.027	+0.028	
4736.031...	*Fe*	3	+0.032	18	10	+0.032	+0.034	
4737.540...	*Cr*	2	+0.034	16	10	+0.034	+0.036	
4739.291...	*Mn*	3	+0.038	3	13	+0.038	+0.040	
4741.718...	*Fe*	3	+0.034	18	12	+0.034	+0.036	
4745.992...	*Fe*	4	+0.034	16	14	+0.033	+0.035	
4752.289...	*Ni*	2	+0.041	16	16	+0.040	+0.042	
4752.613...	*Ni*	3	+0.034	18	10	+0.034	+0.036	
4754.225...	*Mn*	7	+0.022	18	10	+0.022	+0.023	

TABLE I—*Continued*

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ′	Δ′ Reduced to λ 5000	Character or Group
4756.300...	*Cr*	2	+0.026	18	13	+0.026	+0.027	
4756.705...	*Ni*	3	+0.033	18	12	+0.033	+0.035	
4757.771...	*Fe*	2	+0.038	3	13	+0.038	+0.040	
4758.308...	*Ti*	1	+0.034	18	10	+0.034	+0.036	*a*
4759.463...	*Ti*	2	+0.034	3	18	+0.034	+0.036	*a*
4761.718...	*Mn*	3	+0.032	17	11	+0.031	+0.032	
4762.567...	*Mn*	5	+0.027	18	10	+0.027	+0.028	
4762.820...	*Ni*	1	+0.039	3	2	+0.039	+0.040	
4766.050...	*Mn*	3	+0.026	18	8	+0.026	+0.027	
4766.621...	*Mn*	3	+0.028	18	10	+0.028	+0.029	
4773.007...	*Fe*	4	+0.028	3	11	+0.028	+0.029	
4779.634...	*Fe*	1	+0.041	3	7	+0.041	+0.043	
4780.169...	*Co*	2	+0.032	18	11	+0.032	+0.034	Enh.-*Ti?*
4783.613...	*Mn*	6	+0.023	17	12	+0.025	+0.026	
4786.727...	*Ni*	3	+0.021	3	11	+0.022	+0.023	
4787.003...	*Fe*	2	+0.025	18	9	+0.025	+0.026	
4788.952...	*Fe*	3	+0.039	3	15	+0.039	+0.040	
4789.528...	*Cr*	2	+0.033	17	10	+0.034	+0.035	
4789.849...	*Fe*	3	+0.029	18	14	+0.029	+0.030	
4793.045...	*Co*	1	+0.040	12	14	+0.040	+0.042	
4799.598...	*Fe*	1	+0.048	3	21	+0.048	+0.050	
4801.213...	*Cr*	1	+0.047	3	9	+0.047	+0.049	
4803.072...	*Fe*	2	+0.023	3	14	+0.023	+0.024	
4807.179...	*Ni*	2	+0.035	17	8	+0.034	+0.035	
4810.724...	*Zn*	3	+0.035	17	13	+0.035	+0.036	
4813.661...	*Co*	1	+0.038	17	18	+0.038	+0.039	
4820.593...	*Ti*	1	+0.039	13	15	+0.038	+0.039	*a*
4823.697...	*Mn*	5	+0.019	17	12	+0.019	+0.020	
4829.214...	*Ni*	3	+0.036	17	12	+0.036	+0.037	
5123.899...	*Fe*	3	+0.022	16	13	+0.022	+0.021	
5129.336...	*Ti?*	3	+0.019	17	8	+0.020	+0.019	Enh.
5129.546...	*Ni*	2	+0.026	17	10	+0.026	+0.026	
5129.805...	*Fe*	1	+0.035	10	9	+0.033	+0.032	
5131.642...	*Fe*	2	+0.024	20	10	+0.024	+0.023	
5131.942...	*Ni*	1	+0.030	15	12	+0.029	+0.028	
5137.250...	*Ni*	3	+0.021	20	8	+0.021	+0.020	
5137.558...	*Fe*	3	+0.020	20	8	+0.020	+0.019	
5141.918...	*Fe*	3	+0.023	29	9	+0.023	+0.022	
5142.693...	*Fe*	4d	+0.020	28	9	+0.021	+0.020	
5145.371...	*Fe*	1	+0.028	27	10	+0.028	+0.027	
5145.636...	*Ti*	0	+0.026	21	14	+0.027	+0.026	*a*
5146.659...	*Ni–*	3	+0.024	29	9	+0.024	+0.023	
5147.652...	*Ti*	0	+0.029	24	12	+0.028	+0.027	*a*
5148.222...	*Fe*	2	+0.023	29	11	+0.023	+0.022	
5148.410...	*Fe*	3	+0.021	28	8	+0.021	+0.020	
5151.020...	*Fe*	4	+0.016	27	9	+0.016	+0.016	
5152.087...	*Fe*	3	+0.022	27	10	+0.023	+0.022	
5152.361...	*Ti*	0	+0.029	25	10	+0.031	+0.030	*a*
5155.303...	*Ni*	1	+0.030	28	12	+0.030	+0.029	
5155.935...	*Ni*	2	+0.026	30	10	+0.026	+0.025	
5159.231...	*Fe*	2	+0.023	30	9	+0.023	+0.022	
5162.449...	*Fe, C*	5	+0.019	29	9	+0.019	+0.019	
5165.588...	*Fe*	2	+0.020	30	10	+0.020	+0.019	

TABLE I—*Continued*

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ′	Δ′ Reduced to λ 5000	Character or Group
5168.832...	*Ni*	1	+0.026	30	9	+0.026	+0.025	
5171.778...	*Fe*	6	+0.013	29	9	+0.014	+0.013	
5172.856...	*Mg*	20	−0.010	30	12	−0.010	−0.010	
5173.917...	*Ti*	2	+0.019	30	7	+0.019	+0.018	*a*
5176.735...	*Ni*	1	+0.028	30	8	+0.028	+0.027	
5180.233...	*Fe*	1	+0.028	29	11	+0.028	+0.027	
5183.791...	*Mg*	30	−0.013	29	9	−0.013	−0.012	
5186.073...	*Ti*	2	+0.021	30	11	+0.021	+0.020	
5188.079...	*Fe*	1	+0.027	29	10	+0.028	+0.027	
5188.863...	*Ti*	2	+0.015	30	8	+0.015	+0.014	Enh.
5189.018...	*Ca*	3	+0.021	29	10	+0.021	+0.020	
5191.629...	*Fe*	4	+0.014	29	9	+0.014	+0.013	
5192.523...	*Fe*	5	+0.012	30	10	+0.012	+0.012	
5193.139...	*Ti*	2	+0.022	29	9	+0.021	+0.020	*a*
5195.113...	*Fe*	4	+0.017	29	9	+0.017	+0.016	
5195.647...	*Fe*	2	+0.022	29	9	+0.022	+0.021	
5196.227...	*Fe*	1	+0.023	30	9	+0.023	+0.022	
5198.888...	*Fe*	3	+0.022	30	9	+0.022	+0.021	
5210.555...	*Ti*	3	+0.016	30	11	+0.016	+0.015	*a*
5217.552...	*Fe*	3	+0.018	30	9	+0.018	+0.017	
5218.085...	*Fe*	0	+0.029	22	9	+0.028	+0.027	
5218.369...	*Fe*	1	+0.027	29	9	+0.027	+0.026	
5219.875...	*Ti*	0	+0.028	15	8	+0.028	+0.027	*a*
5220.358...	*Ni*	0	+0.023	14	8	+0.023	+0.022	
5221.928...	*Cr*	0	+0.028	17	9	+0.029	+0.028	
5223.351...	*Fe*	0	+0.031	17	9	+0.031	+0.030	
5224.471...	*Ti*	0	+0.028	29	11	+0.028	+0.027	
5225.695...	*Fe*	2	+0.024	30	10	+0.024	+0.023	
5226.707...	*Ti–*	2	+0.020	30	8	+0.020	+0.019	Enh.
5230.030...	*Fe*	4	+0.021	30	10	+0.021	+0.020	
5233.122...	*Fe*	7	+0.007	25	8	+0.007	+0.007	*d*
5235.557...	*Fe*	1	+0.022	29	7	+0.022	+0.021	
5242.658...	*Fe*	2	+0.020	30	10	+0.020	+0.019	
5243.946...	*Fe*	1	+0.029	30	9	+0.029	+0.028	
5247.229...	*Fe*	1	+0.025	29	10	+0.025	+0.024	
5247.737...	*Cr*	2	+0.023	30	10	+0.023	+0.022	
5250.385...	*Fe*	2	+0.029	28	10	+0.028	+0.027	
5250.817...	*Fe*	3	+0.021	30	8	+0.021	+0.020	
5253.633...	*Fe*	2	+0.024	30	12	+0.024	+0.023	
5262.419...	*Ca*	3	+0.020	16	7	+0.020	+0.019	
5263.486...	*Fe*	4	+0.021	30	9	+0.021	+0.020	
5265.729...	*Ca*	3	+0.018	27	7	+0.018	+0.017	
5266.738...	*Fe*	6	+0.013	29	7	+0.013	+0.012	*d*
5281.971...	*Fe*	5	+0.019	26	8	+0.019	+0.018	
5283.802...	*Fe*	6	+0.013	26	10	+0.013	+0.012	
5284.281...	*Ti*	1	+0.026	26	8	+0.026	+0.025	
5288.705...	*Fe*	2	+0.025	25	8	+0.025	+0.024	
5296.872...	*Cr*	3	+0.021	22	10	+0.022	+0.021	
5297.555...	*Cr*	2	+0.021	23	9	+0.021	+0.020	
5298.194...	*Cr*	1	+0.021	22	10	+0.021	+0.020	
5298.455...	*Cr*	4	+0.016	22	9	+0.016	+0.015	
5298.672...	*Ti*	0	+0.023	18	7	+0.022	+0.021	*d?*
5300.929...	*Cr*	2	+0.025	22	10	+0.025	+0.024	

TABLE I—*Continued*

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ′	Δ′ Reduced to λ 5000	Character or Group
5302.480...	*Fe*	5	+0.015	22	11	+0.015	+0.014	
5307.541...	*Fe*	3	+0.022	22	8	+0.022	+0.021	
5324.373...	*Fe*	7	+0.006	21	11	+0.006	+0.006	*d*
5328.236...	*Fe*	8?	+0.007	21	9	+0.007	+0.007	*a*
5335.050...	*Co*	1	+0.026	12	8	+0.026	+0.024	
5340.121...	*Fe*	6	+0.019	22	9	+0.019	+0.018	*d*
5342.890...	*Co*	1	+0.028	13	12	+0.029	+0.027	
5345.991...	*Cr*	5	+0.015	19	10	+0.015	+0.014	
5348.511...	*Cr*	4	+0.017	19	10	+0.017	+0.016	
5349.653...	*Ca*	4	+0.019	19	7	+0.019	+0.018	
5349.928...	*Fe*	1	+0.028	16	14	+0.027	+0.025	
5598.524...	*Fe*	1	+0.019	12	13	+0.019	+0.016	*e*
5598.711...	*Ca*	4	+0.021	12	4	+0.021	+0.018	
5615.520...	*Fe*	2	+0.025	12	6	+0.025	+0.022	
5615.877...	*Fe*	6	+0.011	12	7	+0.011	+0.009	d_1
5624.245...	*Fe*	1	+0.027	4	6	+0.027	+0.023	
5638.488...	*Fe*	3	+0.029	12	8	+0.029	+0.025	d_1
5659.052...	*Fe*	4	+0.013	10	7	+0.011	+0.009	d_1
5682.869...	*Na*	5	+0.028	8	8	+0.028	+0.025	
5688.436...	*Na*	6	+0.026	8	15	+0.026	+0.023	
5805.441...	*Ni*	4	+0.038	26	9	+0.036	+0.031	
5806.950...	*Fe*	5	+0.035	27	14	+0.035	+0.030	
5831.821...	*Ni*	1	+0.032	19	10	+0.034	+0.029	
5838.592...	*Fe*	1	+0.036	12	14	+0.037	+0.032	
5847.221...	*Ni*	1	+0.034	21	11	+0.036	+0.031	
5848.342...	*Fe*	3	+0.035	27	14	+0.035	+0.030	
5853.902...	*Ba*	5?	+0.029	30	10	+0.029	+0.025	
5857.674...	*Ca*	8	+0.025	34	11	+0.025	+0.022	
5857.976...	*Ni*	3	+0.031	32	12	+0.030	+0.026	
5862.582...	*Fe*	6	+0.029	34	10	+0.029	+0.025	
5866.675...	*Ti*	3	+0.035	34	12	+0.035	+0.030	*a*
5890.186...	*Na*	30	−0.008	34	10	−0.008	−0.007	
5893.079...	*Ni*	4	+0.031	34	12	+0.031	+0.027	
5896.155...	*Na*	20	−0.006	34	12	−0.006	−0.005	
5899.518...	*Ti*	1	+0.041	18	9	+0.039	+0.033	*a*
5905.895...	*Fe*	4	+0.025	8	11	+0.023	+0.020	
5910.197...	*Fe*	1	+0.040	15	10	+0.037	+0.032	
5930.406...	*Fe*	6	+0.034	8	12	+0.034	+0.029	
5934.881...	*Fe*	5	+0.035	8	12	+0.035	+0.030	
5948.765...	*Si*	6	+0.037	24	11	+0.036	+0.031	
5949.566...	*Fe*	1	+0.033	19	14	+0.033	+0.028	
5953.386...	*Ti*	1	+0.038	26	16	+0.038	+0.032	*a*
5956.923...	*Fe*	4	+0.035	25	13	+0.035	+0.029	
5975.575...	*Fe*	3	+0.033	21	8	+0.033	+0.027	*b*
5977.007...	*Fe*	4	+0.028	4	6	+0.028	+0.022	*d*
5978.768...	*Ti*	1	+0.037	17	12	+0.037	+0.031	*a*
5983.908...	*Fe*	5	+0.028	4	14	+0.028	+0.023	*d*
5985.040...	*Fe*	6	+0.024	4	10	+0.024	+0.020	*e*
5987.290...	*Fe*	5	+0.016	4	3	+0.016	+0.013	*e*
6003.239...	*Fe*	6	+0.024	4	19	+0.024	+0.020	*d*
6007.540...	*Ni*	1	+0.033	3	14	+0.035	+0.030	
6008.186...	*Fe*	4	+0.027	3	10	+0.030	+0.025	*e*
6008.785...	*Fe*	6	+0.022	4	12	+0.022	+0.018	*d*

TABLE I—*Continued*

λ	Element	Intensity	Δ	No. of Plates	Mean Deviation	Δ'	Δ' Reduced to λ 5000	Character or Group
6013.715...	*Mn*	6	+0.026	3	11	+0.028	+0.023	*d*
6016.861...	*Mn*	6	+0.029	4	11	+0.029	+0.024	*d*
6022.016...	*Mn*	6	+0.022	4	6	+0.022	+0.018	*d*
6027.274...	*Fe*	4	+0.021	3	8	+0.023	+0.019	*b*
6042.315...	*Fe*	3	+0.029	4	9	+0.029	+0.024	Enh.
6056.227...	*Fe*	5	+0.030	4	10	+0.030	+0.025	*e*
6065.709...	*Fe*	7	+0.018	3	3	+0.016	+0.013	*b*
6393.820...	*Fe*	7	+0.017	25	10	+0.017	+0.013	*b*
6400.217...	*Fe*	8	+0.016	24	8	+0.015	+0.012	*d*
6400.528...	*Fe*	2	+0.026	24	11	+0.026	+0.020	
6408.233...	*Fe*	5	+0.021	25	8	+0.021	+0.017	*d*
6411.865...	*Fe*	7	+0.019	25	9	+0.019	+0.015	*d*
6420.169...	*Fe*	4	+0.025	25	10	+0.025	+0.020	
6421.570...	*Fe*	7	+0.023	25	8	+0.023	+0.018	*b*
6431.066...	*Fe*	5	+0.021	25	9	+0.021	+0.017	*b*
6439.293...	*Ca*	8	+0.018	24	4	+0.018	+0.014	
6450.033...	*Ca*	6	+0.020	25	10	+0.020	+0.016	
6455.820...	*Ca*	2	+0.036	44	12	+0.035	+0.029	
6471.885...	*Ca*	5	+0.028	44	10	+0.027	+0.022	
6494.004...	*Ca*	6	+0.020	47	9	+0.020	+0.017	
6495.213...	*Fe*	8	+0.019	48	11	+0.017	+0.014	*b*
6496.688...	*Fe*	2	+0.038	30	12	+0.037	+0.030	
6497.128...	*Fe*	4	+0.020	30	9	+0.020	+0.016	
6499.168...	*Fe*	1	+0.039	30	12	+0.037	+0.031	
6499.880...	*Ca*	4	+0.030	29	11	+0.030	+0.024	
6563.045...	H_α		−0.064	29	26	−0.064	−0.050	
6569.460...	*Fe*	5	+0.039	28	14	+0.037	+0.030	
6573.030...	*Ca?*	1	+0.042	29	13	+0.041	+0.032	
6575.270...	*Fe*	2	+0.034	27	11	+0.032	+0.026	
6586.550...	*Ni*	1	+0.039	30	12	+0.037	+0.030	
6593.161...	*Fe*	6	+0.026	30	10	+0.024	+0.020	*b*
6594.121...	*Fe*	4	+0.029	30	10	+0.029	+0.022	
6597.807...	*Cr*	1	+0.041	30	17	+0.041	+0.031	
6633.995...	*Fe*	2	+0.045	30	18	+0.045	+0.034	
6643.876...	*Ni*	5	+0.033	30	12	+0.033	+0.025	

DISCUSSION

From a brief examination of the absolute displacements in the fourth column of Table I, it is evident that the larger displacements are associated with the longer wave-lengths. The mean displacements of the lines of iron in the violet and yellow-red regions from intensity 1 to 8 are given for each intensity in the following table. In the upper section the displacements are as measured. In the lower section, when reduced to a common wave-length, λ 5000.

TABLE II

Displacements and Wave-Length

Region	Mean λ	Intensity								Mean
		1	2	3	4	5	6	7	8	
Violet..........	4017	0.022	0.020	0.014	0.014	0.013	0.011	0.008	0.006	0.014 Å.
Yellow-red.....	6121	.032	.030	.032	.024	.028	.024	.019	.016	.026
Violet..........	4017	.026	.024	.019	.018	.017	.013	.011	.008	.017 Å.
Yellow-red.....	6121	0.027	0.024	0.026	0.021	0.023	0.020	0.015	0.013	0.021

The means of the unreduced displacements are violet 0.014 Å., red 0.026 Å.; of the reduced displacements, 0.17 Å., and 0.021 Å., respectively—results that seem decisively in favor of an effect varying as the wave-length. The spectra of the two regions were of necessity photographed separately, and there was no over-lapping series of plates by which the relative displacements could be exactly determined. In each region the plates varied among themselves, due to slight changes in the position of the slit of the spectrograph in reference to the edge of the penumbra and to the fact that they do not always pertain to the same spot. In the means from a large number of plates, these accidental variations tend to neutralize each other. The violet region is represented by 34 plates and 81 lines, the yellow-red region, by 66 plates and 43 lines. In view of the probability that the effect of accidental variations is largely eliminated, the differences between the absolute displacements in the two regions may be considered to be fundamental and the decrease from 0.012 to 0.004 Å. in the mean difference when the displacements are reduced to a common wave-length indicates that the observed differences are due to the Doppler effect, and that we are dealing with real movements of gases in the reversing layer. The values used in the comparison were deduced from all the lines measured, and no account was taken of the effect arising from the different groups of iron lines or from the different spectral regions, other than that due to change in wave-length.

A fact equally striking is the systematic variation of the displacements with the intensities of the Fraunhofer lines. For lines of the intensities considered, the displacements progressively decrease with the increase of line intensity. In Table III the mean displacements of 193 iron lines of intensities 1 to 8 are given under their respective intensities.

TABLE III

DISPLACEMENTS AND LINE INTENSITIES REDUCED TO λ 5000

Mean λ	Intensity								No. Lines	Mean Interval
	1	2	3	4	5	6	7	8		
4017	0.026	0.024	0.019	0.018	0.017	0.013	0.011	0.008	81	0.003 Å.
4992	0.030	0.026	0.026	0.025	0.018	0.016	0.006	0.007	69	0.003
6121	0.027	0.024	0.026	0.021	0.023	0.020	0.015	0.013	43	0.002
Wtd. mean	0.028	0.025	0.023	0.021	0.019	0.016	0.012	0.009	..	0.003
Vel. km/sec.	1.68	1.50	1.38	1.26	1.14	0.96	0.72	0.54	..	0.18

For these lines the wave-lengths are longer on the limb edge of the penumbra than on the center edge when the spot is between the center of the sun and the limb, and the flow of the gases is outward and tangential to the solar surface, and on the assumption that, on the whole, the weaker lines originate at the lower level the velocity outward increases with the depth.

Though the lines of a given intensity in a given spectral region originate at some mean depth, it is not probable that the same mean depth would be found when widely differing spectral regions are compared. In Table IV the residuals are given for the three regions included in the investigation. These are obtained by deducting the mean displacements from the displacement for each of the three regions.

The consistently negative residuals for the violet region and the positive residuals for the yellow-red region point to a lower level in the region of longer wave-length for the lines of the same intensity. The mean level of lines in the red is about two units of intensity lower than in the violet; lines of intensity 4 in the red region being then at the level of lines of intensity 2 in the violet, and similarly for lines of other intensities. Such a difference is the natural consequence of the scattering of light by small particles, which varies inversely as the fourth power of the wave-length. From this it would result that we see into the sun to a greater depth in the red than in the violet. If this difference in level is taken into account when the displacements in the violet and yellow-red regions are compared after reduction to a common wave-length, the agreement is very close. In Table V the first intensity refers to the violet, the second to the yellow-red, so that the comparison is now between lines at approximately the same levels. The means of the unreduced displacements are 0.016 Å. and 0.024 Å., of the reduced displacements 0.0195 Å. and 0.0197 Å., respectively. The sum of the differences violet minus yellow-red is −0.001 Å.

TABLE IV

RESIDUALS

Intensity	Violet λ 4000	Blue-Green λ 5000	Yellow-Red λ 6100
1	−0.0018	+0.0014	+0.0014
2	− .0008	+ .0019	+ .0005
3	− .0043	+ .0031	+ .0036
4	− .0030	+ .0039	− .0004
5	− .0025	− .0006	+ .0040
6	− .0033	− .0004	+ .0037
7	− .0010	− .0055	+ .0032
8	−0.0013	−0.0019	+0.0041
Mean	−0.0023	+0.0002	+0.0026

TABLE V

DISPLACEMENTS AND WAVE-LENGTHS

Comparisons between Lines at Same Levels

Intensities	1, 3	2, 4	3, 5	4, 6	5, 7	6, 8
Violet	0.026	0.024	0.019	0.018	0.017	0.013
Yellow-red	0.026	0.021	0.023	0.020	0.015	0.013
Difference	0.000	+0.003	−0.004	−0.002	+0.002	0.000

For lines of intensities exceeding 10, the displacements are small or negative and then increase numerically with the elevation. The data are summarized in Table VI.

The negative sign indicates that the wave-lengths of the corresponding lines are shorter on the limb edge of the penumbra than on the edge toward the center of the sun's image, and therefore denotes an inflow of the gases at the level of these lines with velocities increasing with the elevation.

TABLE VI

Displacements of Strong Lines (λ 5000)

Element	*Mg*	*Si*	*Al*	*Sr*	*Ca* (λ 4227)	*H* (H_δ)
Intensity..........	10	12	15–20	8	20	40
Displacement......	+0.002	0.000	0.000	−0.002	−0.002	−0.005
Vel. km/sec	+0.12	0.00	0.00	−0.12	−0.12	−0.30

Element	*Na* (D_1, D_2)	*Mg* (b_2, b_1)	*H* (H_γ)	*Ca* (H_2, K_2)	*H* (H_α)	*Ca* (H_3, K_3)
Intensity..........	20–30	20–30	20	....	40	....
Displacement......	−0.006	−0.012	−0.033	−0.044	−0.050	−0.063
Vel. km/sec	−0.36	−0.72	−1.98	−2.64	−3.00	−3.78

The series of displacements in the case of the iron lines when arranged according to the intensities forms a practical and convenient scale for determining the relative levels in the solar atmosphere at which the lines of other elements are produced. Extending the series to include *Fe* 00 and *Fe* 15–40, which then covers the entire range of iron lines, we have the following iron scale:

TABLE VII

The Iron Scale (λ 5000)

Intensity	00	0	1	2	3	4	5	6	7	8	10	15–40
Displacements..	0.034	0.030	0.028	0.025	0.023	0.021	0.019	0.016	0.012	0.009	0.004	0.000
Vel. km/sec	2.04	1.80	1.68	1.50	1.38	1.26	1.14	0.96	0.72	0.56	0.24	0.00

The extreme values at either end depend upon very few lines and are consequently of relatively low weight. On but one plate was it possible to measure the *Fe* lines of intensity 0 and 00. This gave the values 0.029 Å. and 0.036 Å. for the two intensities. The values found by extrapolation from the values 1–8 are 0.031 and 0.033 Å. The means of the observed and extrapolated values have been used to extend the scale. Three difficult iron lines, intensities 15, 20, and 40, gave the value 0.000 as a mean of closely agreeing values. The displacements and the corresponding velocities are, throughout, the relative values for the two edges and are to be divided by two, so that the maximum velocity of outflow indicated by the means is 1 km per second. The maximum outward velocity observed in the case of any line was 2.2 km per second.

RADIAL VELOCITIES AND THE SOLAR VORTEX

When the velocities radial to the vortex axis and tangential to the solar surface are plotted as abscissae with elevations above the continuous spectrum background as ordinates upon any convenient scale, a very striking distribution is shown. Such a vertical section through the axis of the vortex is given in Fig. 2. In the lower portion representing the effective levels in the reversing layer, the velocities are mainly those given by the iron lines; in the upper portion, which refers to the chromosphere, the identification of the lines is given in connection with the plotted velocities. The ordinates are entirely arbitrary and are only meant to indicate the increasing velocities of inflow with increasing elevation above the region of velocity-inversion and the increasing velocities of outflow as the depth increases below this level. At the right are given some elevations taken from Jewell's table of which he says: "I have tried to give a fair and conservative estimate determined from several plates."[1] In the diagram are also given some preliminary and fragmentary results obtained in the course of an extended investigation of pressures in the solar atmosphere now being carried on, but upon which considerable reliance can be placed when it is a question of the variation of pressure with depth.

The distribution of the plotted velocities might lead one at first to consider them as representing the inflow and outflow of the gases in the case of an actual vortex. This comes partly from the apparent symmetry of the diagram, but the scale is very different above and below the level of inversion. The lower portion is some 3500 km thick while the upper is over 20,000 km in thickness, so that the actual height of the upper portion is several times that of the lower.

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[1] *Publications of the U.S. Naval Observatory*, **4**, Appendix I, 299–307.

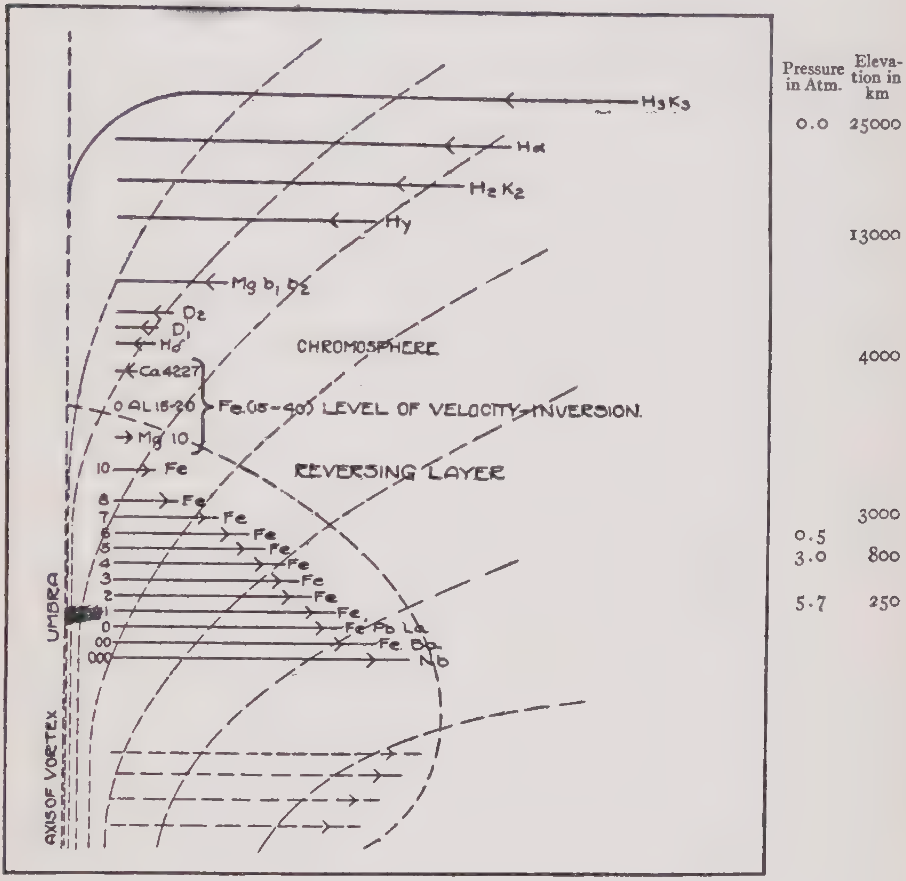

FIG. 2.—Vertical section of reversing layer and chromosphere showing the distribution of radial velocities in sun-spots. The lengths of the solid lines are proportional to the radial displacements of the corresponding Fraunhofer lines. The arrows indicate the direction of flow. The rounded head of the cyclonic disturbance is suggested by the broken-line curve enveloping the outward velocities. The broken lines with arrows refer to possible velocities below the accessible levels. The lines of force of the magnetic field are indicated in the usual way.

There are three lines of argument militating against the view that these velocities form the velocity system of an actual vortex.

In the first place, the composition of the material flowing outward in the lower portion is very complex, containing, as will be shown in a later paper, at least 27 elements—in fact, all elements the lines of which have been investigated in this paper—while the inflowing material is calcium, hydrogen, magnesium, sodium, and probably some of the higher level vapors of iron, aluminium, and strontium. It will be noticed that the level of velocity inversion is about where the customary division is made between the chromosphere and the reversing layer. Secondly, the masses involved in the inflow and outflow are quite different. An approximate value for the mass which flows across the boundary into the spot from the chromosphere may be found as follows. The velocity in this region decreases with increase of the density of the inflowing gases, so that the center of the mass of the inflowing material is located in the level where the velocity is low. For an approximation, the level may be assumed to be that of magnesium, b_1, b_2, where the velocity of inflow is 0.36 km per second. The pressure is very low at the level of this velocity, perhaps 0.1 terrestrial atmosphere, since in the upper reversing layer it is much less than 1 atmosphere and rapidly decreases upward. The mass resting upon an area of 1 sq. cm$=m=P/G=100/27.6=3.6$ grams, where G is the solar gravitation constant.

The mean radius of the penumbrae of the spots under investigation is 11,250 km, so that the velocities found are the velocities normal to the surface of a cylinder of this radius. The quantity of material crossing the boundary in one second may be found by considering a shell of the given radius whose thickness is numerically equal to the velocity per second inward across the boundary, and upon the cross-section of which the surface density is the mass of the homogeneous atmosphere per square centimeter, that is, $2\pi Rm\Delta R$. In the present case $R=11{,}250$ km, $\Delta R=0.36$ km, and $m=3.6$ grams. The mass so calculated is $29\pi\times10^{13}$ grams.

In like manner an approximate value of the mass that flows across the boundary outward into the reversing layer may be found. The velocity in the reversing layer increases with the increase of density, and both increase rapidly with depth, so that the center of mass of the outflowing material is in the level where both velocity and density are high. It may be assumed to be at the level of *Fe* 00 where the velocity is 1 km per second. From the rapid increase of pressure with depth the pressure may be assumed as 10 terrestrial atmospheres. The mass of the reversing layer resting upon an area of 1 sq. cm is then $360-3.6=356$ grams, and the mass moving outward per second is $8\pi 10^{15}$ grams, and the ratio of the inflowing to outflowing mass is 276.

The third reason is based upon the energy crossing the boundaries above and below the level of inversion, in the chromosphere and in the reversing layer respectively. The ratio MV^2 (reversing layer)/MV^2 (chromosophere) reaches the approximate value 2000. It is true that these are approximate values and only roughly approximate, but from the order of the ratios it is evident that the outflow into the reversing layer is not fed by the inflow from the high level, and that both the mass and the energy supplied from above are only small fractions of that flowing out below, while in a true vortex there is an equilibrium between the two activities.

In the terrestrial cyclone and especially in the types represented by the tornado, hurricane, and water-spout, it is known that in the upper portion the air is moving outward. Moore, in describing the hurricane, says:

> In the cirrus cloud level, 10,000 to 12,000 m. above the sea, the clouds are observed to move rapidly outward in all directions. The outward moving clouds represent the radial velocities in the upper levels of the dumb-bell vortex while the inner wind velocities found on the sea-level occur in the plane which truncates the vortex at some distance above the theoretical lower boundary plane. . . . . The radial velocity diminishes up to the middle plane and then increases outward; the tangential velocity increases up to the middle plane and then gradually diminishes. Near the center the centrifugal force is so great, on account of the rapid rotation of the air in the inner rings, that there is practically a calm central core, something like 20 or 30 miles in diameter.[1]

The outward velocities in the reversing layer at the outer boundaries of the penumbrae of sun-spots may then, with great probability, be referred to a low-lying vortex, since the outflow is not supplied from the higher levels. In the upper part of a dumb-bell or trumpet-shaped vortex the radial velocities increase with higher levels and in the theoretical discussion the radial velocities approach infinite limits and become asymptotic to the plane of reference. In the reversing layer the velocities increase with the depth, and it is true that the radial velocities outward in cyclones increase with height above the middle plane, but in the nature of things these outward movements of the air after reaching a maximum must decrease with greater height, by propagating themselves into and by entraining the overlying air, so that the region of disturbance would be dome-shaped above and the surface of zero radial velocity would have the dumb-bell form. This spreading and rounded head is characteristic of the whirling columns of steam, smoke, and ashes that rise from volcanoes and great furnace stacks.

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[1] *Descriptive Meteorology*, pp. 162–163.

The complete radial velocity system in the upper section of a solar vortex is indicated in the diagram by including the dotted abscissae, and the section of the surface of zero radial velocity by the enveloping curve. From this point of view the level reached by the spectrograph is still above the region of outwardly decreasing velocities, and such a region is as yet inaccessible to the spectroscope directly, since the level reached by this method of sounding the solar atmosphere cannot be deeper than the level at which the weakest Fraunhofer lines originate. Iron and vanadium lines of intensity 00 still indicate by their displacements outward velocities increasing with the depth and it is not probable that lines of 2 intensities less, the weakest in Rowland's table, will reach the level of decreasing velocities. In the levels accessible to spectroscopic investigations the tangential velocities in the vortex have disappeared; their maximum value would occur at far lower levels. The same is true in the case of the vertical component, as both reach their maximum values in the middle plane of the vortex. This explains the failure to find definite indications of such velocities from displacements due to the Doppler effect. It is possible that by employing the lines of lowest level evidences of such velocities may be found in occasional spots.

The inflow of the chromospheric gases seems to follow, in part, at least, from the general downward movement of these gases.

This settling effect was shown for magnesium and sodium by Perot and Lindstreedt,[1] and for calcium in my paper on the general circulation of calcium.[2] The temperature in or immediately above the umbrae of spots is lower than in the surroundings, and this would produce in the overlying gases an added tendency to fall. As a result of one or both effects a downward flow would set in over the umbrae. Such an effect is indicated by the early observations of Respighi, who states as follows the results deduced from his observations made upon the border of the sun's disk:

> 1. In the neighborhood of the spots the chromosphere (*strato rosato*) is rather low, quite regular, and intensely bright.
>
> 2. Upon the exact locality of a spot or rather over its nucleus the chromosphere is generally very low and sometimes totally wanting.[3]

The down-flowing gases would be caught in the current of the outflowing vapors in the upper portion of the vortex, and carried outward into the upper reversing layer, and the circulation once started would tend to continue. As in the case of fluids flowing into a sink, a whirl would in general be produced. The direction of this whirl would have no necessary hydrodynamical connection with the direction of rotation in the underlying vortex, since the tangential motion in the vortex ceases before reaching the lower reversing layer, and therefore is not propagated into the overlying region as the radial motions are. It is probably this upper whirl that has given the indications of inward flow and of vortex motion in spots that the visual observations, such as those of Secchi, occasionally show, and very probably the spectroscopic evidences of inflow and rotation of the high-level calcium vapor shown by my observations[4] refer to this pseudo-vortex. These observations, when considered from this point of view, are more easily interpreted. The wave-length of K_3 was measured at the center and over flocculi, penumbrae, and umbrae. The most striking feature of these measurements is the remarkable agreement of the means for the separate regions with the general mean from 500 observations, which indicates a downward movement of approximately 1.1 km per second. A downward movement of the calcium vapor showed at all times in 88 per cent of the spots, varying in velocity from 0.68 km to 2.2 km with a general mean of 1.3 km per second. Four spots showed a motion of rotation of inflowing vapor with radial components for K_2 and K_3 of 1.24 km and 2.00 km per second, and tangential components of 0.98 km and 1.6 km per second, respectively. The small amount by which the downward velocity over spots exceeded that over the general surface, the fact that some spots gave no spectroscopic evidence of descent over the umbrae, and the small number of spots that showed vortex motion seemed surprising from the point of view that the observations refer to the real vortex, and especially in view of the fact that every spot is the seat of a magnetic field, as the results from Mr. Hale's discovery of the Zeeman effect in sun-spot spectra have shown. And there appears to be no other explanation than that the field is due to the existence of a vortex. But if a vortex, why do the surface indications so frequently fail to give evidence of it through spectroscopically observed displacements of the Fraunhofer lines or the vortical structure of the H_α flocculi in spectroheliograms? More rarely still do the conspicuous H_2 flocculi show any radial structure. The difficulties are in great measure removed by considering these as secondary and superficial effects depending upon elevation, the properties of the elements, and the field at these great distances from the underlying vortex. The cool region above the umbra acts as a sink into which the chromospheric vapors descend with or without the formation of a whirl, and from which they are discharged into the upper reversing layer. The whirl when formed may bear no relation to the direction of rotation, and only a very loose relation to the intensity of the underlying vortex. The conditions favoring the production of vortex structure in the inflowing gases are quite different at the levels of the H_α and H_2 flocculi. These levels are widely separated, the level of the H_α flocculi is probably some thousands of kilometers above the level of the H_2 flocculi, which are not far from the level of the upper reversing layer. At the level of the H_α flocculi the conditions are: inward velocity high, magnetic field strong, inertia of ions small; and at the level of the H_2 flocculi the conditions are: inward velocity low, magnetic field stronger, inertia of ions large.

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[1] *Comptes Rendus*, **152**, 1367, 1911; **154**, 326, 1912.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 48; *Astrophysical Journal*, **32**, 36–82, 1910.

[3] *American Journal of Science*, 3d Series, **1**, 1871.

[4] *Contributions from the Mount Wilson Solar Observatory*, No. 54; *Astrophysical Journal*, **34**, 57–78, 131–153, 1911.

From an electrodynamic point of view, a view suggested by Professor Störmer, the high inward velocity of the hydrogen, due mainly to the general inflow, and the small inertia of the hydrogen ions are conditions favorable to the production of stream-line structure in the H_α flocculi by a magnetic field which may act mainly as a directing force upon the inward moving ions. At the level of the H_2 flocculi the relatively quiescent state of the gases and the great inertia of the calcium ions, the *Ca*-ion having forty times the mass of the *H*-ion, are conditions very unfavorable to the formation of stream lines at this level. The force exerted by the field upon the ions varies directly as their velocity which, at this level, is very small, since the H_2 flocculi are not far above the level of velocity inversion, and the velocity produced by the field varies inversely as the mass of the ion.

From a hydrodynamic point of view also the conditions are favorable to the production of stream lines in the H_α flocculi, as the hydrogen is flowing into the spot, but at the level of the H_2 flocculi the motion is small or nil, and stream lines are absent because there is little or no flow into the spot at this level. Bearing upon the quiescent condition of the gases producing the H_2 flocculi are some data I obtained when looking for evidence of vertical motion in the bright calcium vapor over the flocculi around spots. It had been assumed in the literature of the subject that this bright material was rising. The wave-lengths of the bright K_2 line over various regions when on the meridian were found to be as follows:[1]

Over general surface	3933.641
Over flocculi	.664
Over penumbrae	.665
Over umbrae	.682
In the arc	.667

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 54; *Astrophysical Journal*, **34**, 57–78, 131–153, 1911.

There is a rise of the calcium vapor over the general surface and a descent over the umbrae of 1.97 km and 1.3 km per second respectively, but over the flocculi and penumbrae an almost stationary condition obtains.

The occasional occurrence of vortical motion of the calcium vapor and the stream-line structure of the hydrogen flocculi may be coincident with the presence in spots of especially strong magnetic fields. A comparison of the field strength in spots showing these phenomena with that in spots in which these phenomena are absent throws some light upon this interesting question.

In the "Summary of the Results of the Study of the Mount Wilson Photographs of Sun-Spot Spectra,"[1] Mr. Adams gives a list of lines for which the separations in the spot spectra have been measured. The separations given by the lines upon Plate T 219 are given in a separate column, as they were distinctly greater than for the other spots. The Greenwich numbers for the spots are 6393, 6441, 6511, 6577. From nine lines which were measured as doublets upon all the plates the ratio of the field given by T 219 to the mean of the other plates is 1.3. The umbra of this spot was very black and large and the total magnetic flux was much greater than for either of the other spots. It was 2.5 times the mean for the other spot, when the areas of the umbrae and field intensities are both taken into consideration. The spot is No. 6577, a spot remarkable for its numerous returns, as it persisted during seven rotations of the sun. Of this spot I said in my paper on the "Motion and Condition of Calcium Vapor over Spots and Other Special Regions": "In the case of Spot 6577, when it was near the west limb, the north edge of the penumbra gave the shorter wave-length. When it appeared at the east limb as 6592 the south edge gave the shorter wave-length."[2] In both cases the rotation of the calcium vapor was clockwise. The H_α spectroheliogram shows marked radial structure of the hydrogen flocculi. Spot 6441 was next in size to Spot 6577, and showed hydrogen structure and at times great activity. It was with this spot that I obtained the series of exposures showing a dark hydrogen flocculus being drawn into the spot. Six of these exposures are shown in Plates XXXVII, XXXVIII, XXXIX, of Mr. Hale's original paper on the solar vortices.[1] Spot 6393 showed no definite structure on the H_α spectroheliograms, but large bright eruptive areas following in the train of the spot. Spot 6511 gave no definite structure on an excellent plate that showed remarkably interesting structure about other spots on the sun's disk at the same time.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 40; *Astrophysical Journal*, **30**, 86–126, 1909.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 54; *Astrophysical Journal*, **34**, 57–78, 131–153, 1911.

In the type of vortex in which the data of the present paper seem to find their interpretation, there is an enormous flux of energy from the vortex into and below the lower reversing layer. The mechanical energy of motion is rapidly transformed into other forms, as the velocity decreases rapidly with distance. The question of how rapidly will be taken up in a later investigation. The form and distribution of this energy in the surrounding region is another interesting question. In the umbrae of sun-spots we now recognize the presence of hydrides and oxides, as shown by the investigations of Fowler, Hale, Adams, and Olmsted. Owing to the low temperature in spots, it is possible that these compounds undergo condensation also. They will be carried with the general flow outward into the reversing layer where decomposition will take place at the expense of a part at least of the energy of the moving gases. But the greater part of this energy will be available for raising the temperature of these low-lying regions, and not only will the temperature be raised, but there will probably be a heaping-up of very hot material around the spot, which would explain the presence and the formation of the faculae. Such a piling-up of air around the cyclone center is evidenced by the high barometer around the center of disturbance.[2] Secchi's sketch of a spot and faculae, when near the limb on March 4, 1866, is suggestive of such a heaping-up of hot material around a spot. In my paper on the "Motion and Condition of Calcium over Special Regions"

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 26; *Astrophysical Journal*, **28**, 100, 1908.

[2] Reye, *Die Wirbelstürme, Tornados, und Wettersäulen in der Erd-Atmosphäre*, p. 135.

I was led to infer in the explanation of the character of the H_2 spectroheliograms at different levels that the faculae may be considered as regions from which a disturbance capable of increasing their emissive power is propagated into the overlying gases, and that these regions may be of higher temperature absolutely, or apparently so from their being elevated above a portion of the surrounding vapor, and that there is probably a piling-up of calcium vapor over the faculae.[1] The result of the flux of material and energy outward from the spot would be to produce both of these effects, and the enormously increased emission on the part of the calcium vapor producing the bright H_2 and K_2 components would be caused by the high temperature prevailing around the spot. The relative emissive power of the H and K lines increases rapidly with temperature, as King has shown.[2] The intensely bright and quiet chromospheric layer observed near spots by Respighi may be referred to the high temperature of the region surrounding spots.

The measurement of the line displacements given in Table I has been made by Miss Ware. I wish to express my appreciation of the patience and skill required in the long series of measurements and of her interest in the progress of the work.

SUMMARY

1. The observations reported in the present paper are in entire accord with Mr. Evershed's hypothesis that the displacements considered are due to a movement of the solar vapors tangential to the solar surface and radial to the axis of the spot vortex.

2. The proportionality between the displacements and wavelengths shows that the phenomenon is due to the Doppler effect and that we are dealing with an actual flow of the material of the reversing layer out of spots and of the chromospheric material into spots.

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[1] *Contributions from the Mount Wilson Solar Observatory*, No. 54, 40; *Astrophysical Journal*, **34**, 148, 1911.

[2] *Contributions from the Mount Solar Observatory*, No. 32; *Astrophysical Journal*, **28**, 389, 1908.

3. The increase of displacements indicating an outward flow with the decrease in the intensity of the lines of the reversing layer and the increase of the displacements indicating an inward flow with increasing intensity of the high-level lines of the chromosphere find their explanation in differences of level. The outward velocities increase with distance below a neutral level, the inward velocities increase with distance above this neutral level or the level of velocity inversion.

4. The vertical distribution of the velocities shows at high levels an inflow into spots and at low levels an outflow. A consideration of the quality and the quantity of the material and of the amount of energy involved in the two movements indicates that they do not of themselves form a vortex system.

5. The type of vortex indicated is that of the terrestrial tornado or hurricane. There is a whirling upward rush of material from the interior of the sun, which spreads out radially with rapidly decreasing velocity, tangential to the solar surface, and entrains with it the gases of the reversing layer. The actual vortex is deep-seated, the outflow into the reversing layer being a portion of the upper part of it, the inflow from the chromosphere being a secondary effect, a superficial indication of the underlying vortex in which the magnetic field originates.

6. The secondary phenomenon shows sometimes vortex motion of the high-level calcium vapor, visible evidences of vortex movements, and stream-line structure of the H_α flocculi, depending upon the strength of the magnetic field and the rotational energy of the underlying vortex.

7. The absence of stream-line structure in the H_2 flocculi follows from the quiescent state of the calcium vapor producing these flocculi. This shows no vertical motion, and the flocculi are near the level of zero velocity along the solar surface.

8. The flux of gases into and below the lower portion of the reversing layer would cause a piling-up of material, the temperature of which would be raised by the rapid transformation of mechanical energy into heat, and the increased emission of the calcium vapor would then be a temperature effect.

9. When the displacements of lines in the red and violet of

equal solar intensities are compared, the lines in the violet show the smaller displacements and therefore originate at higher levels, a consequence of the scattering of light.

10. The displacements of the iron lines arranged in the order of intensities from 00 to 10 form a regular descending scale for determining the relative levels in the solar atmosphere at which the lines of like intensities of other elements have their origin.

Mount Wilson Solar Observatory
December 23, 1912

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